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Pinkerton et al.

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(45) **Date of Patent:** ***Oct. 20, 2015**

(54) **ELECTRICALLY CONDUCTIVE MEMBRANE PUMP/TRANSDUCER AND METHODS TO MAKE AND USE SAME**

(2013.01); *H04R 1/24* (2013.01); *H04R 1/2811* (2013.01); *H04R 31/003* (2013.01); *H04R 2307/023* (2013.01); *H04R 2307/025* (2013.01); *H04R 2307/027* (2013.01)

(71) Applicant: **Clean Energy Labs, LLC**, Austin, TX (US)

(58) **Field of Classification Search**

USPC 381/190, 191, 165
See application file for complete search history.

(72) Inventors: **Joseph F Pinkerton**, Austin, TX (US);
William Neil Everett, Cedar Park, TX (US)

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(73) Assignee: **Clean Energy Labs, LLC**, Austin, TX (US)

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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This patent is subject to a terminal disclaimer.

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(21) Appl. No.: **14/309,615**

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(22) Filed: **Jun. 19, 2014**

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(65) **Prior Publication Data**

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Primary Examiner — Davetta W Goins

Assistant Examiner — Amir Etesam

Related U.S. Application Data

(74) *Attorney, Agent, or Firm* — Greenberg Traurig, LLP;
Ross Spencer Garsson

(63) Continuation-in-part of application No. 14/161,550, filed on Jan. 22, 2014.

(57) **ABSTRACT**

(51) **Int. Cl.**

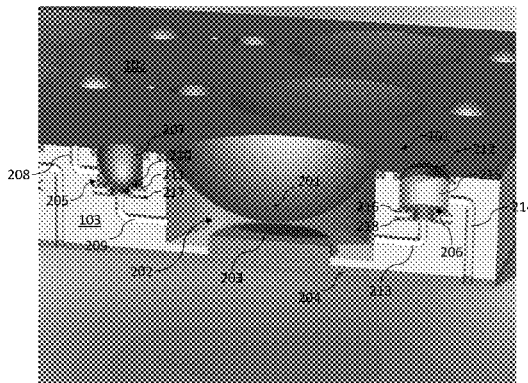
H04R 25/00	(2006.01)
H04R 19/02	(2006.01)
H04R 17/00	(2006.01)
B06B 1/02	(2006.01)
H04R 7/04	(2006.01)
H04R 1/24	(2006.01)
H04R 1/28	(2006.01)
H04R 31/00	(2006.01)

An improved electrically conductive membrane pump/transducer. The electrically conductive pump/transducer includes an array of electrically conductive membrane pumps that combine to generate a desired sound by moving a membrane (such as a membrane of PDMS), a piston, and/or by the use of pressurized airflow in the absence of such a membrane or piston. The electrically conductive membranes in the array can be, for example, graphene-polymer membranes. The electrically conductive pump can include mid-range, tweeter, and sub-woofer speakers.

(52) **U.S. Cl.**

CPC **H04R 19/02** (2013.01); **B06B 1/0292** (2013.01); **H04R 7/04** (2013.01); **H04R 17/00**

15 Claims, 44 Drawing Sheets



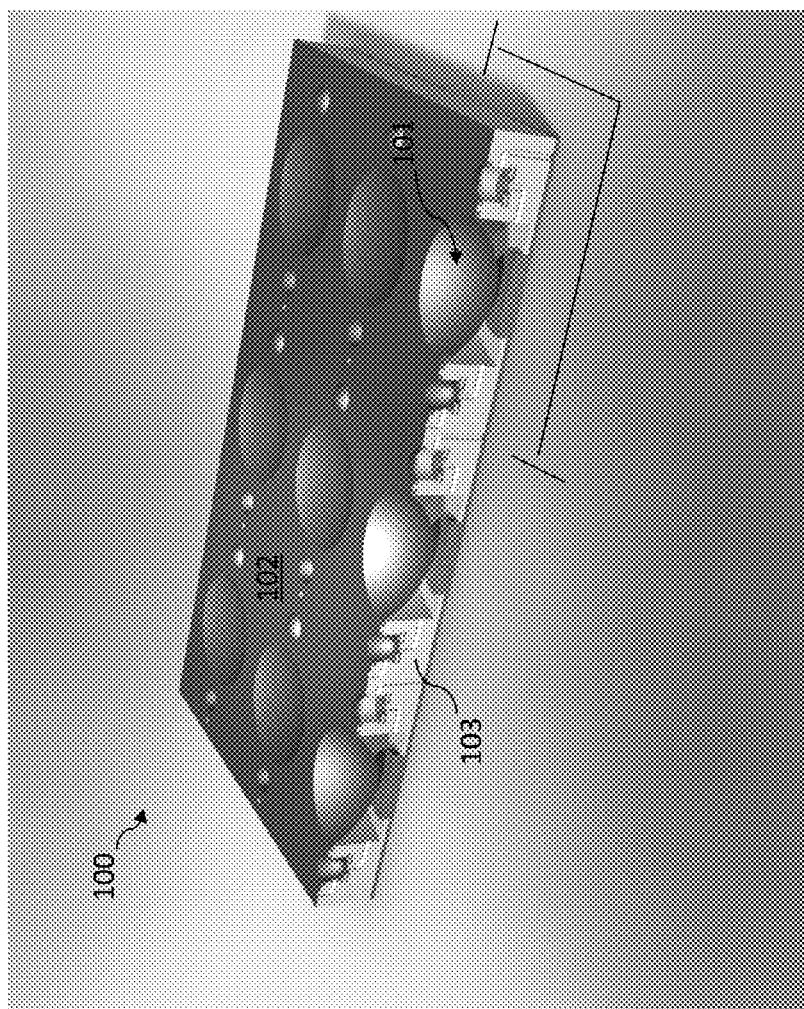


FIG. 1

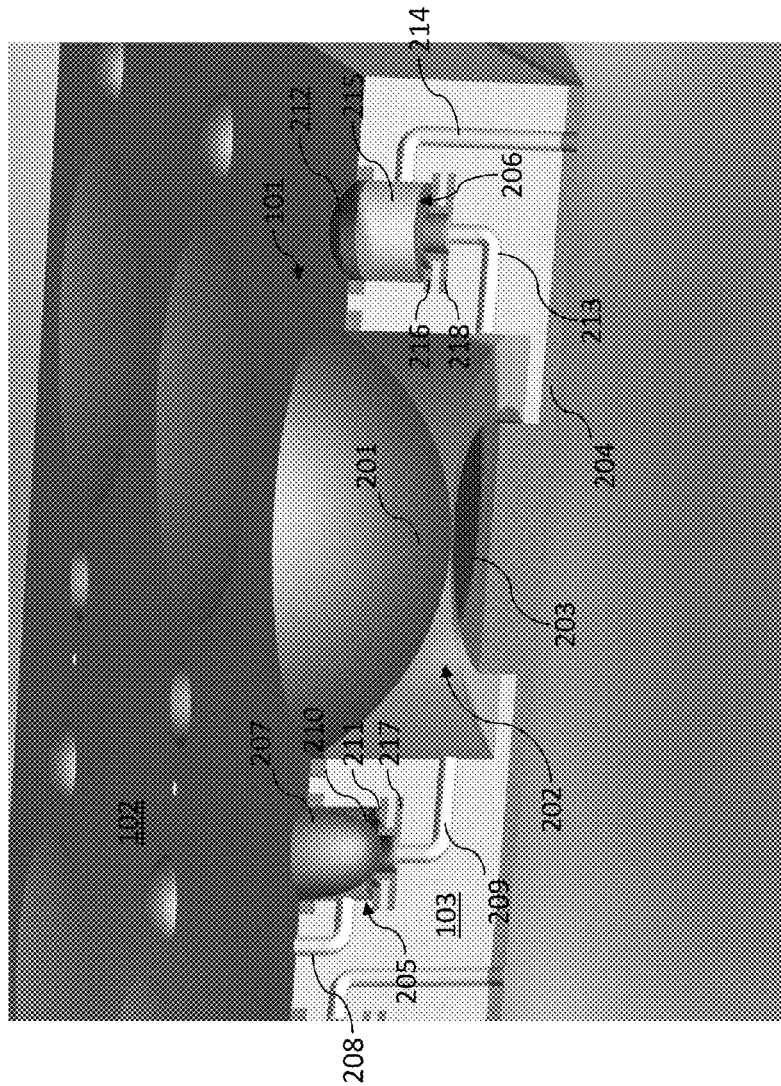


FIG. 2

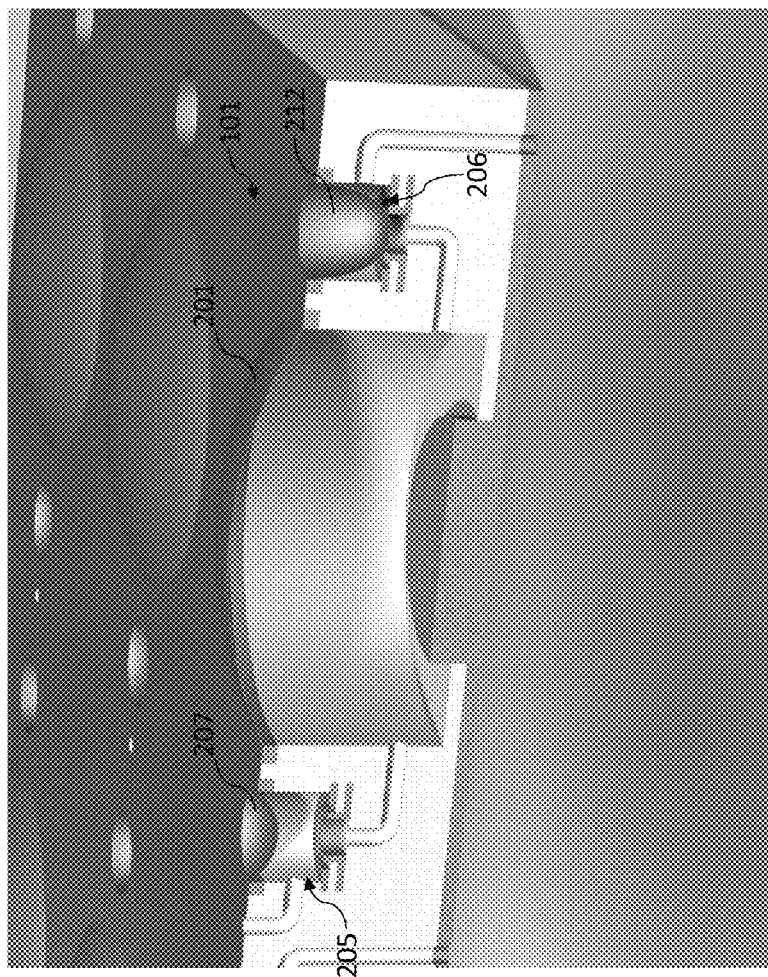


FIG. 3

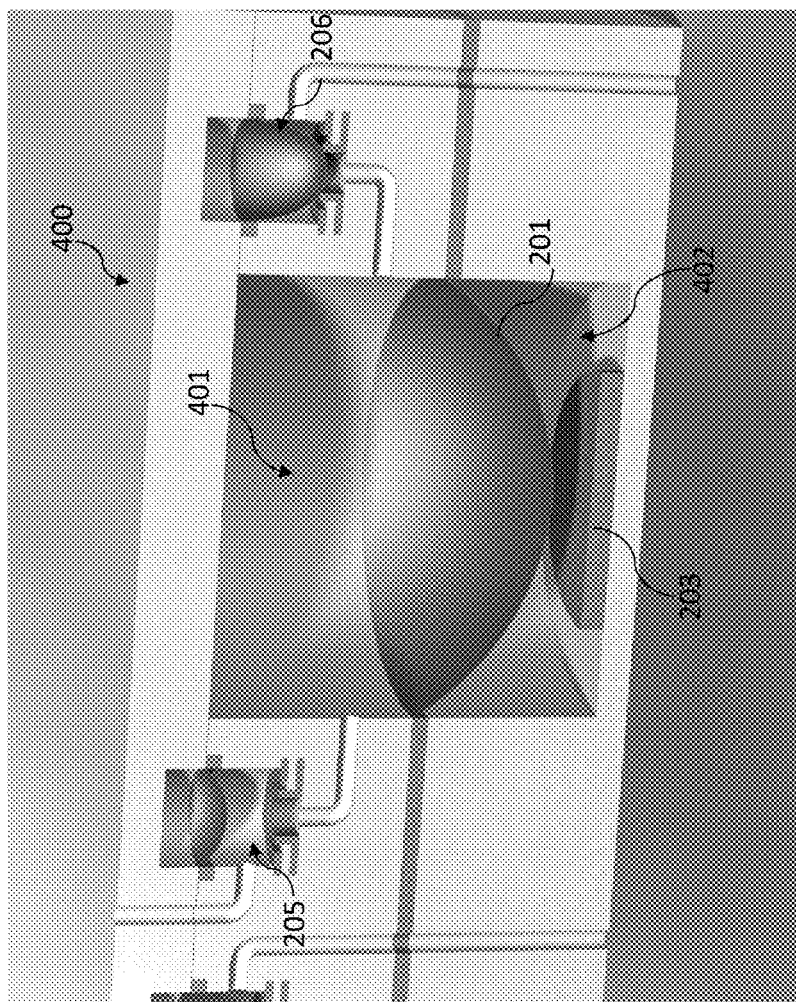


FIG. 4

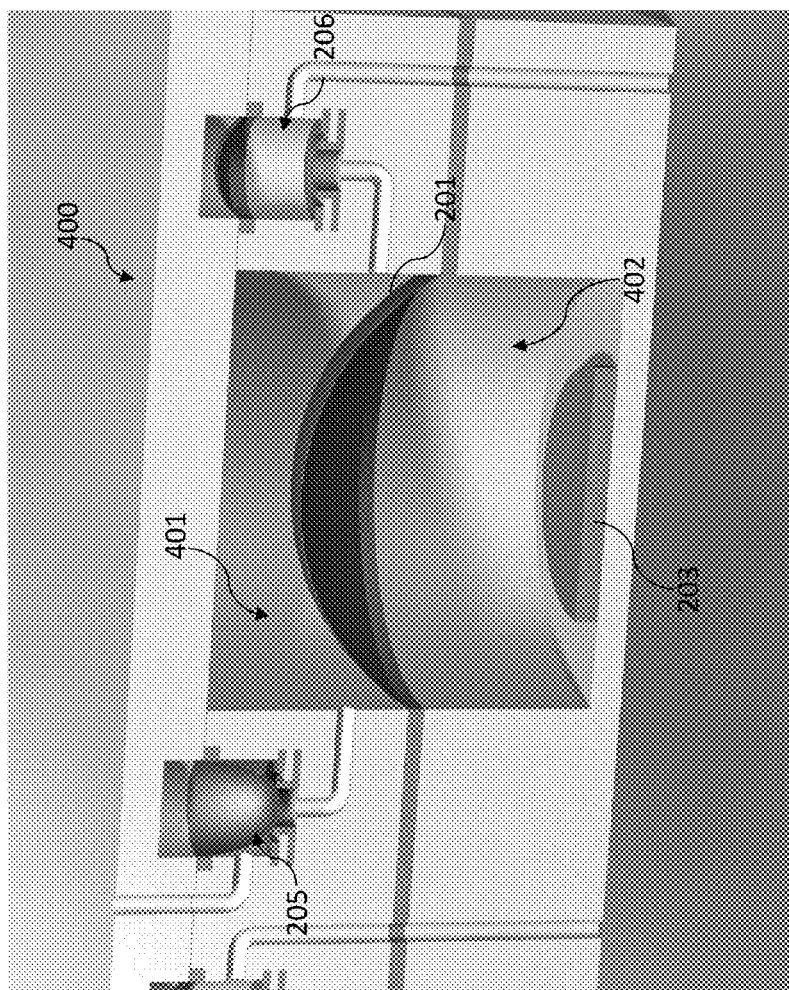


FIG. 5

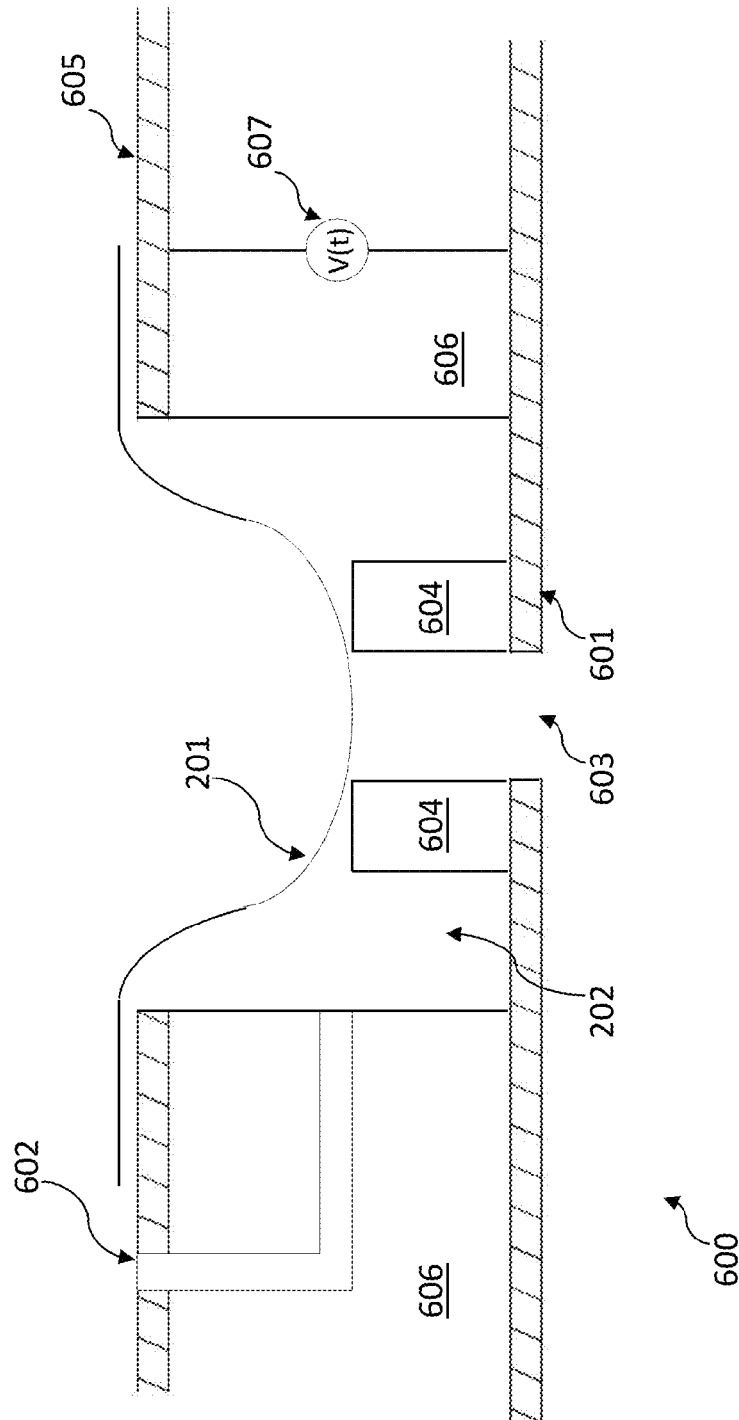


FIG. 6

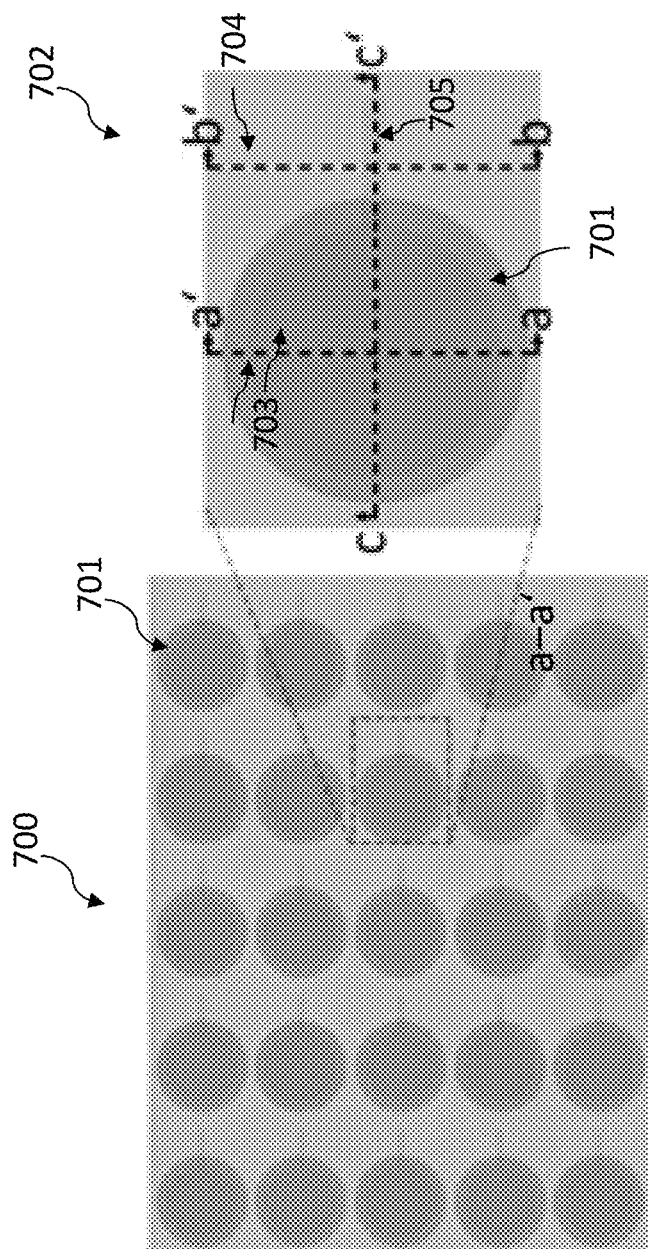


FIG. 7

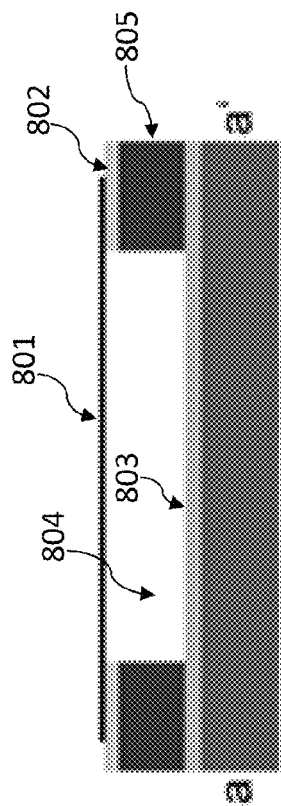


FIG. 8A

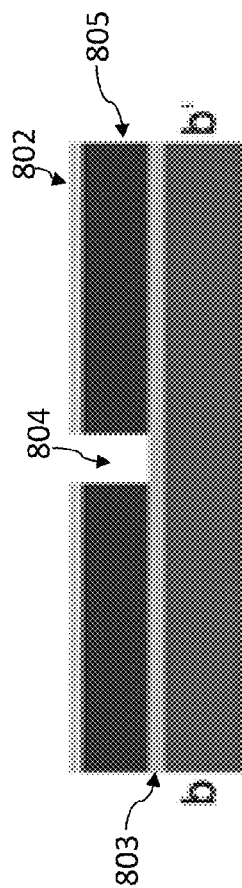


FIG. 8B

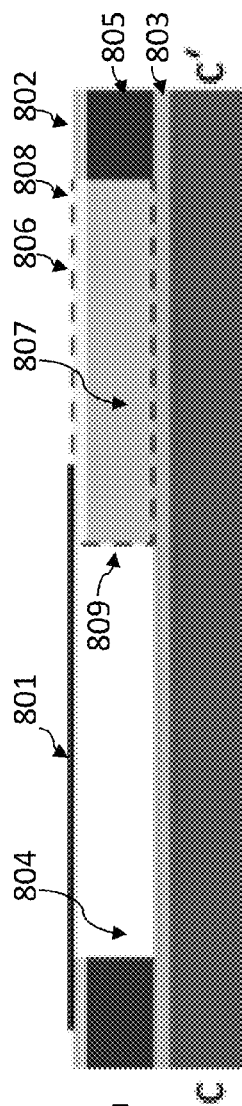


FIG. 8C

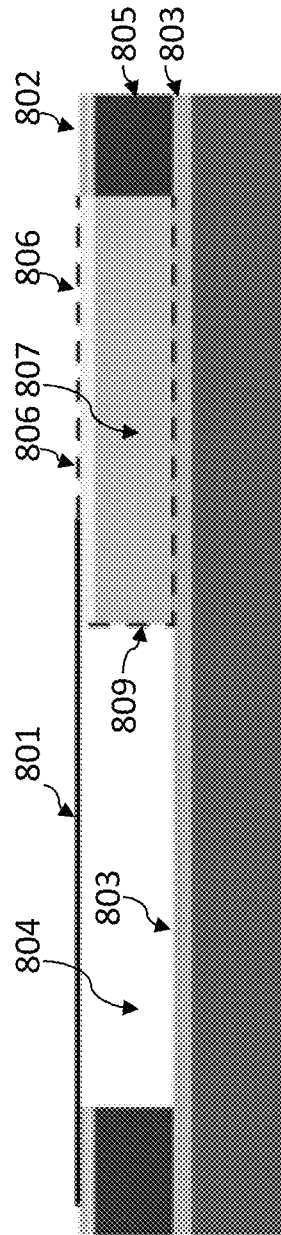


FIG. 9A

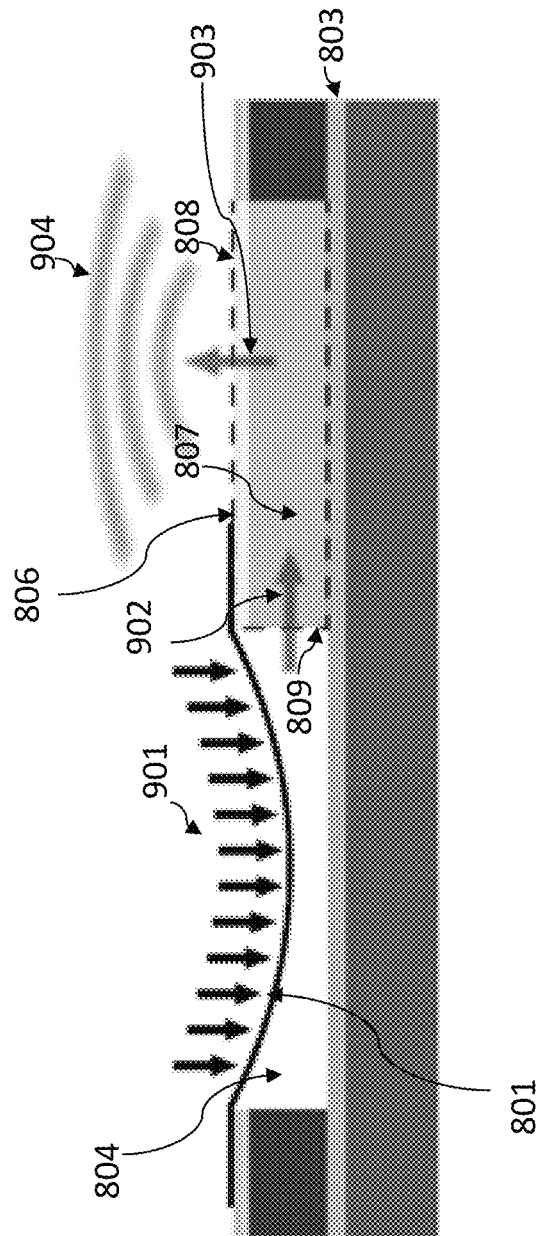


FIG. 9B

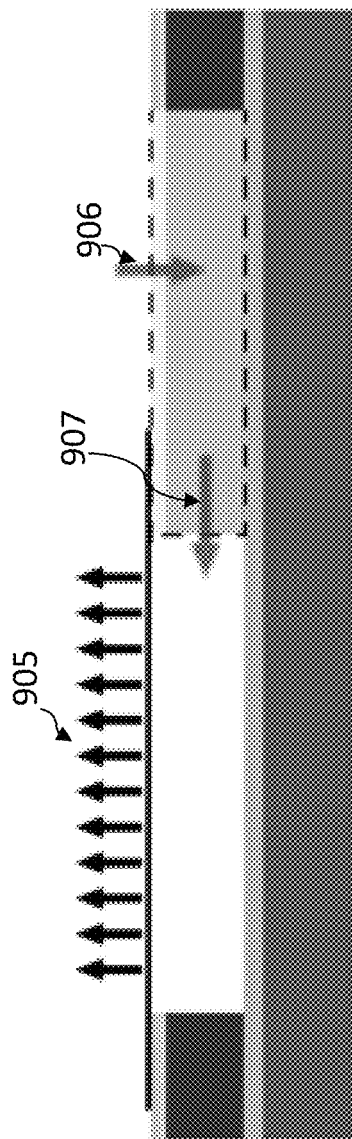


FIG. 9C

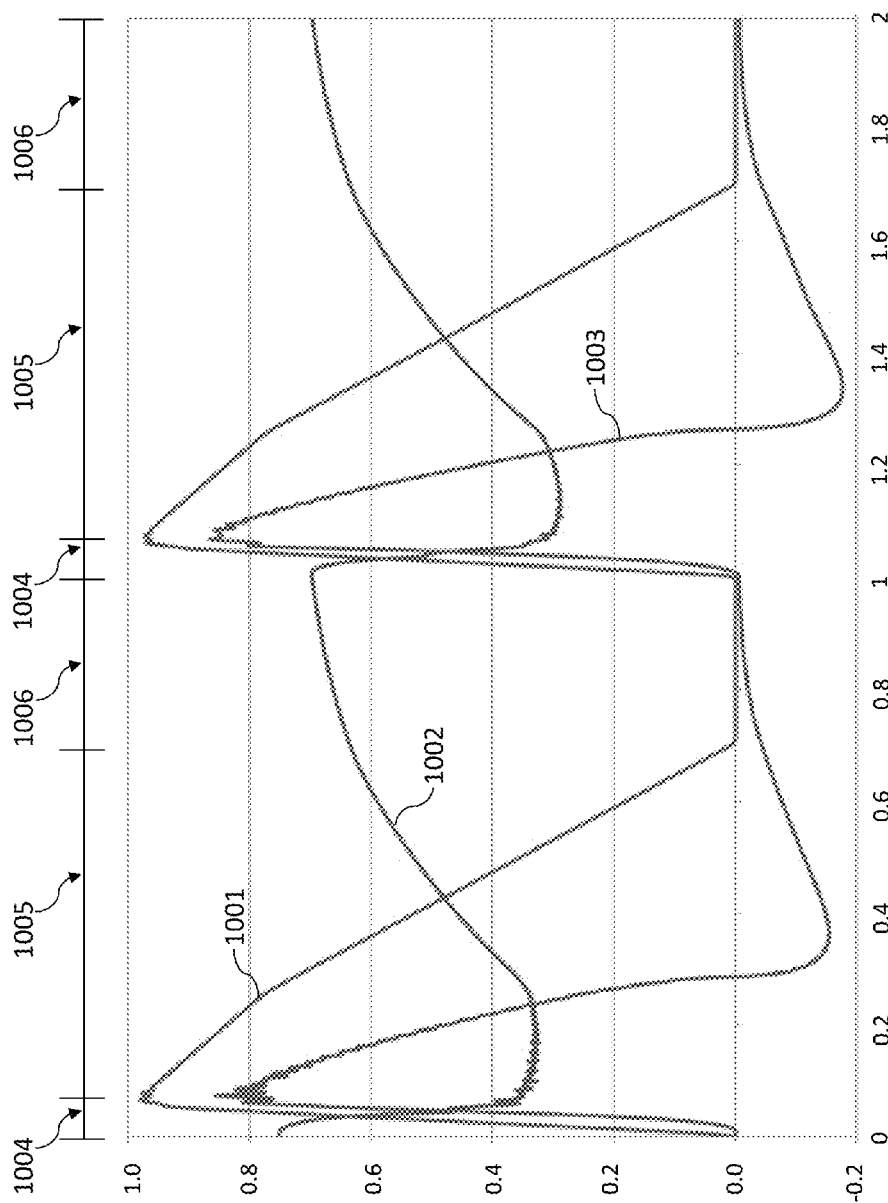


FIG. 10

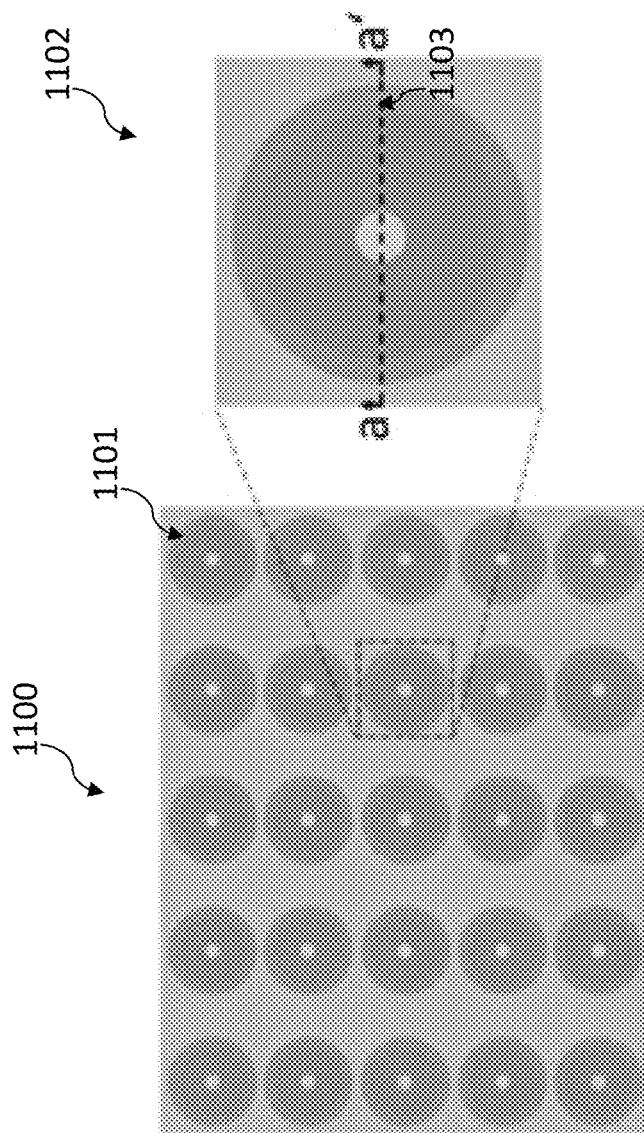


FIG. 11

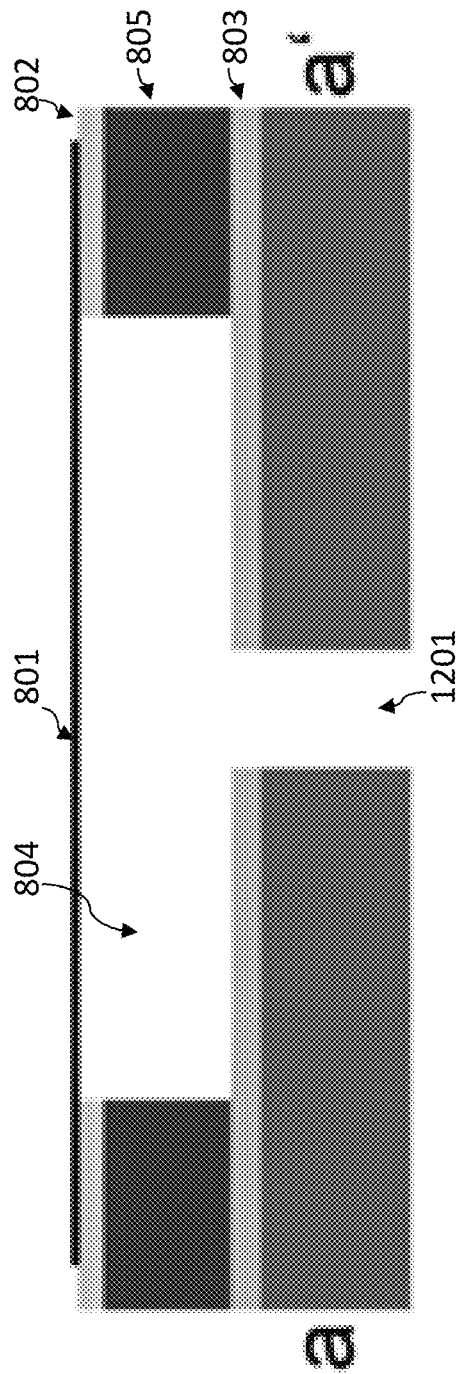


FIG. 12

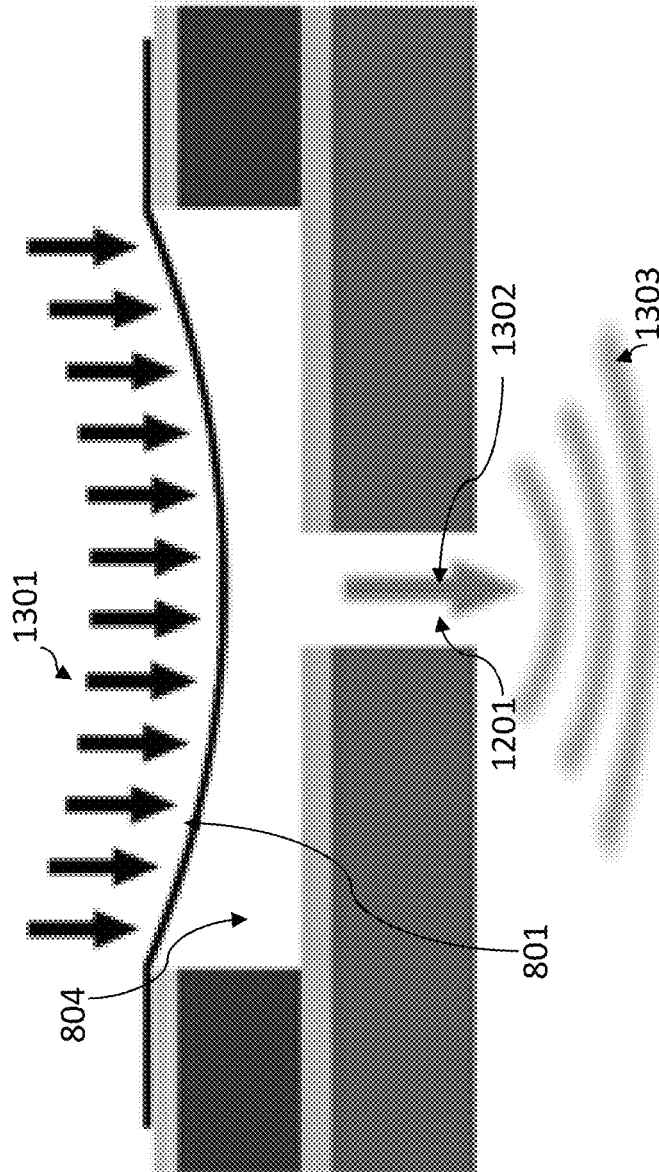


FIG. 13A

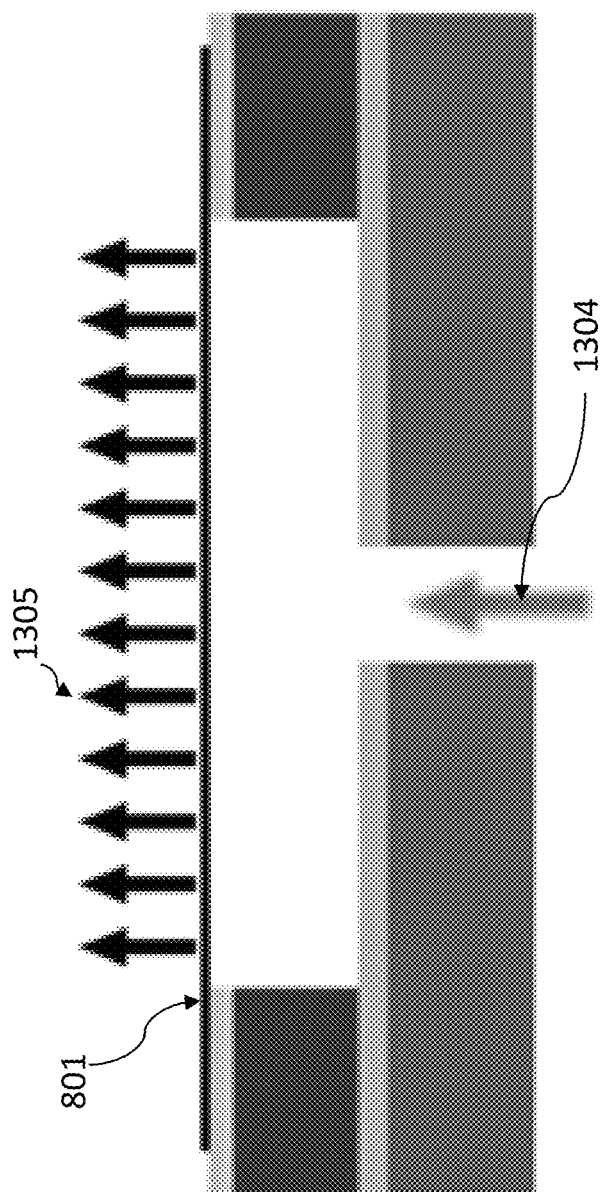


FIG. 13B

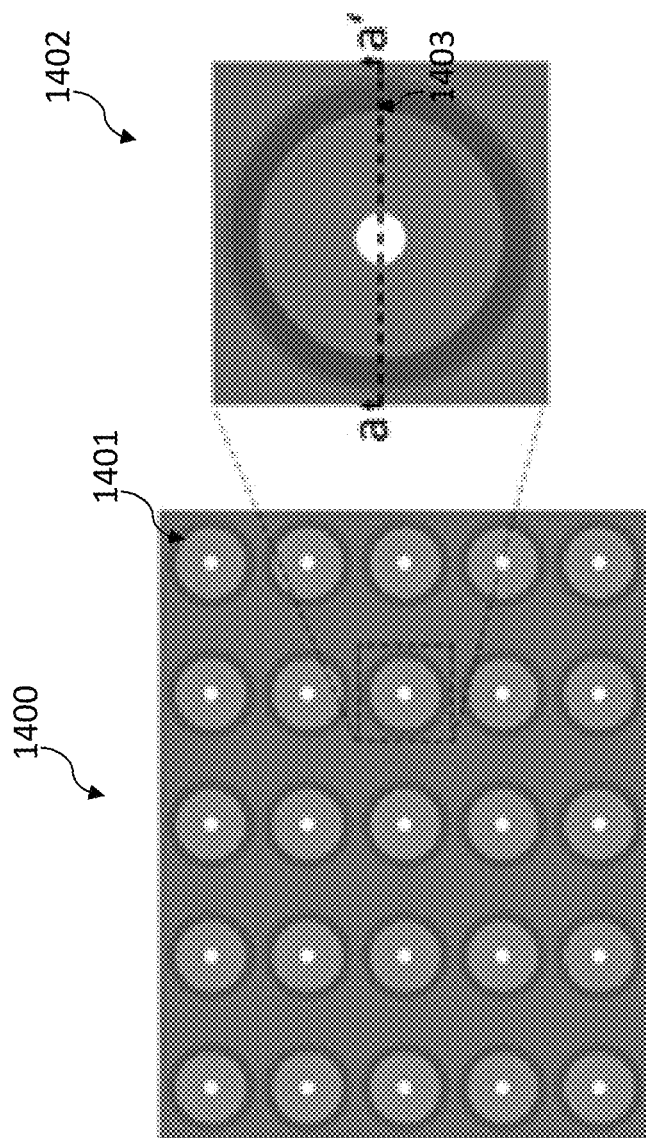


FIG. 14

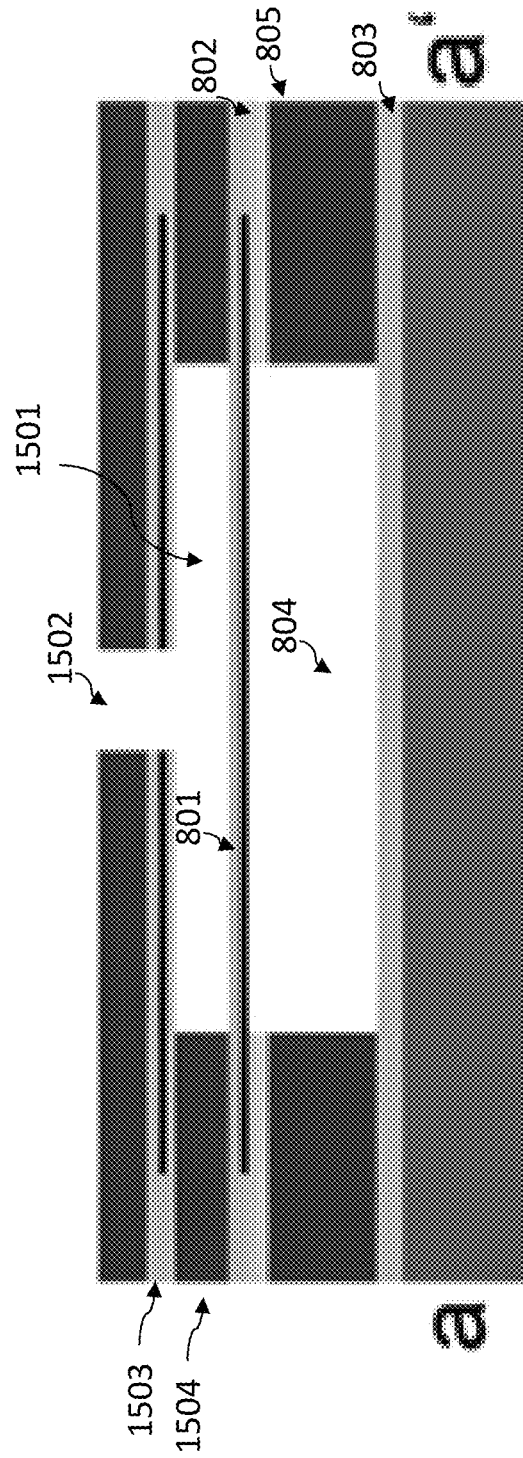
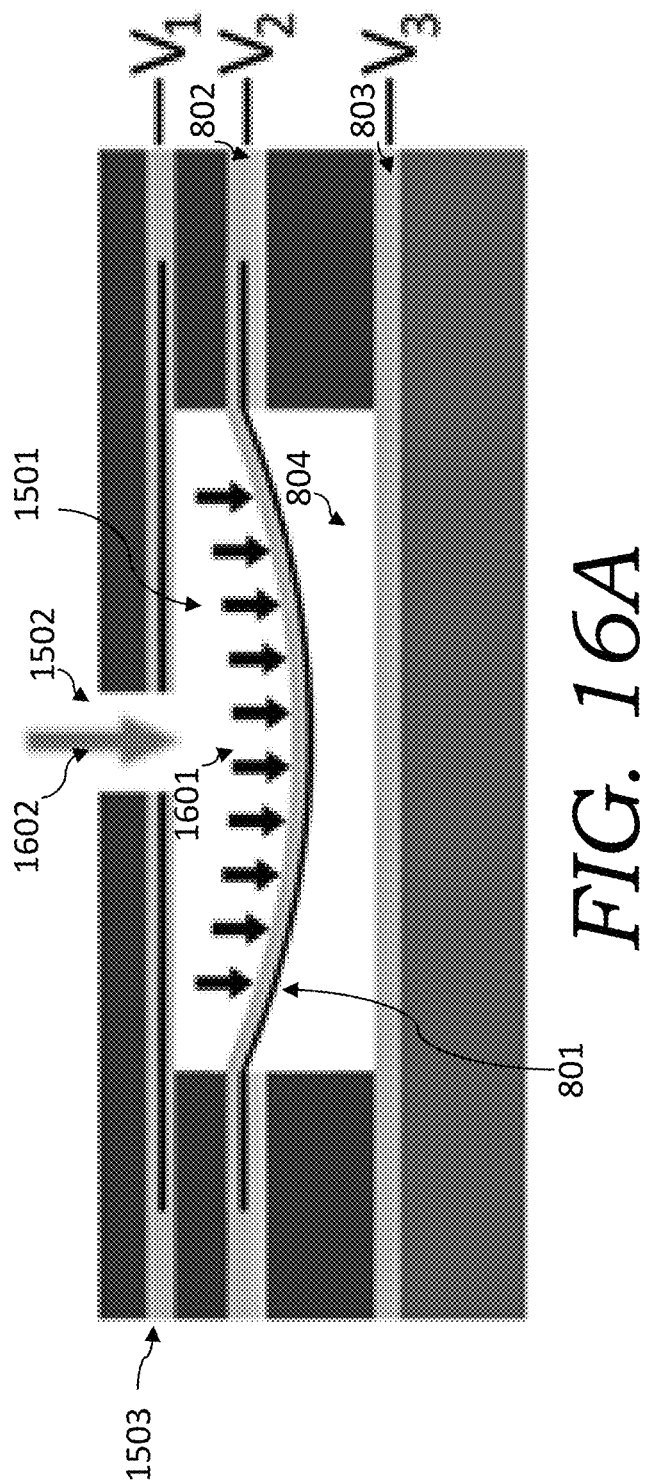
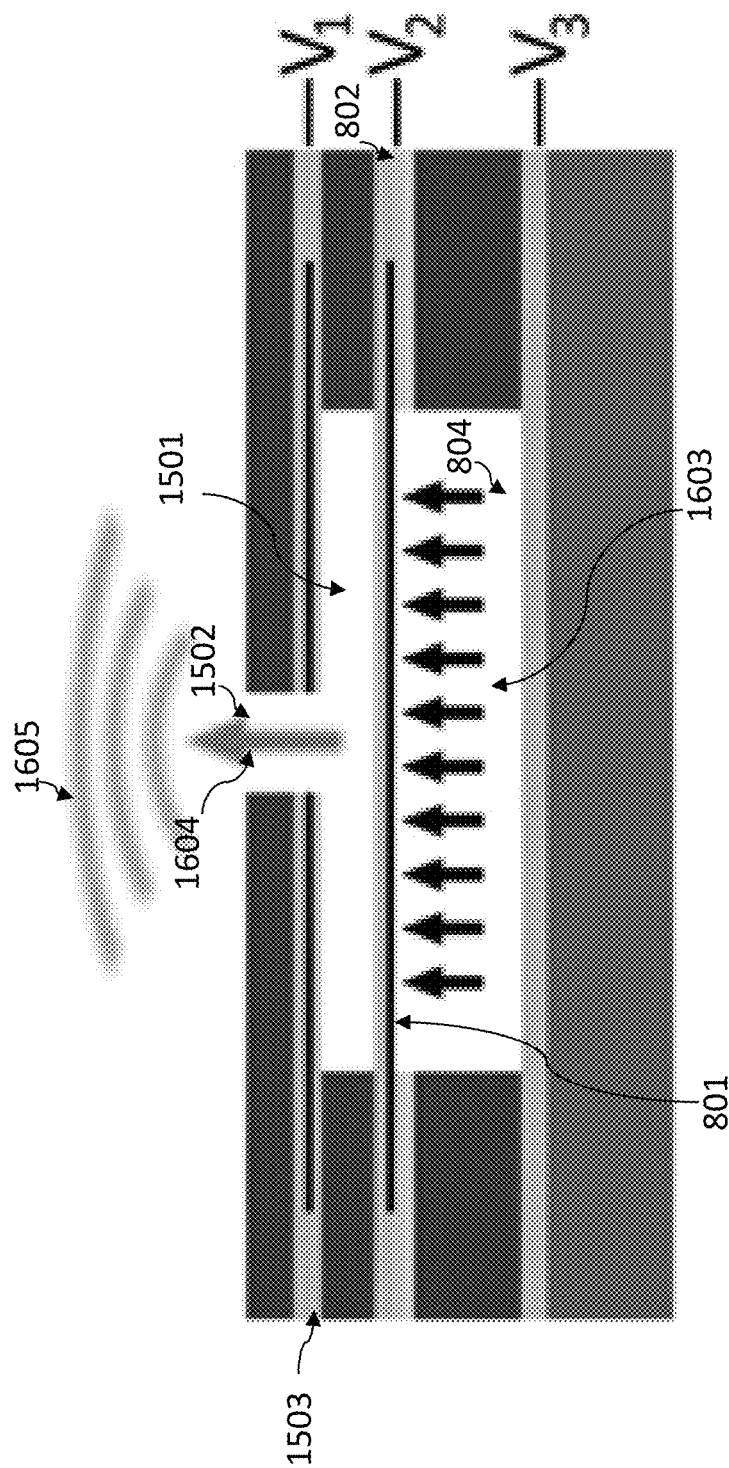


FIG. 15





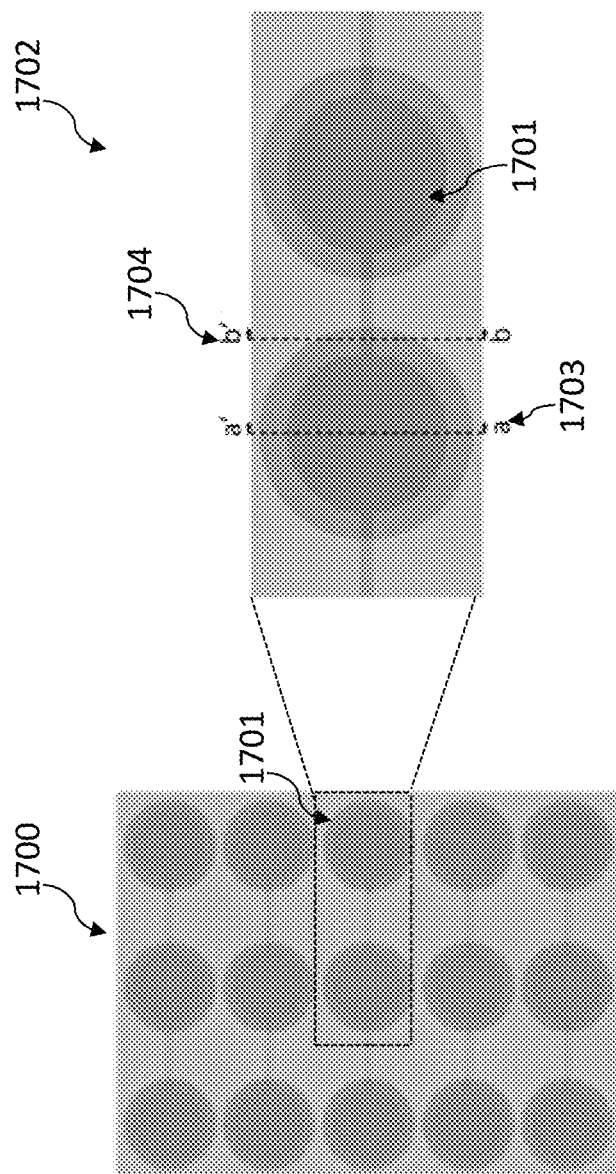


FIG. 17

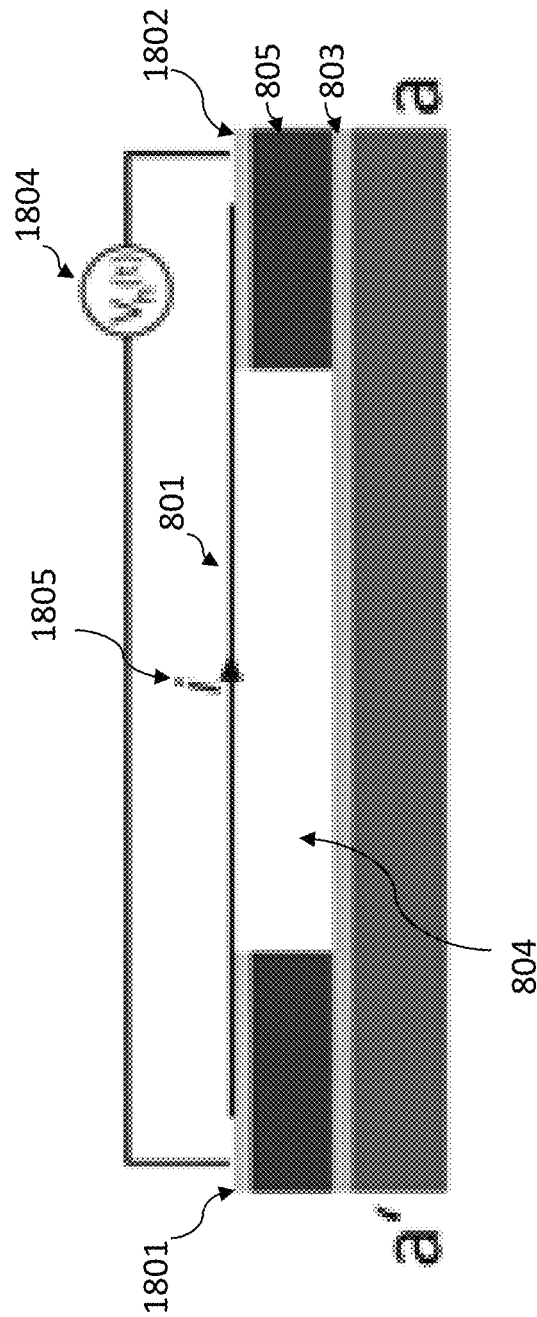


FIG. 18A

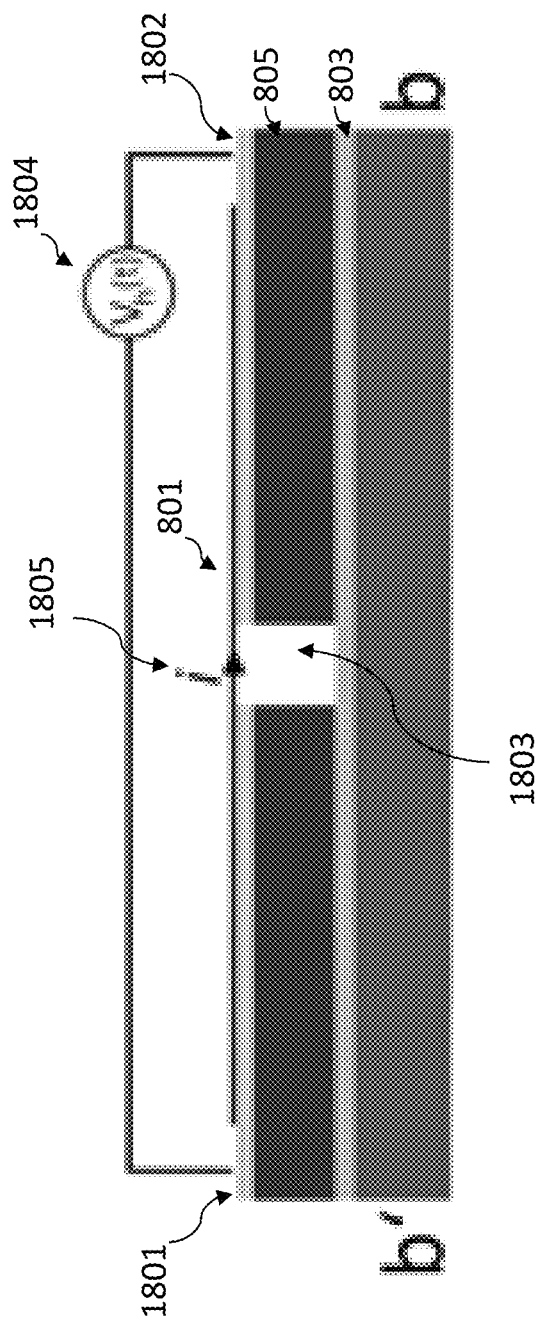


FIG. 18B

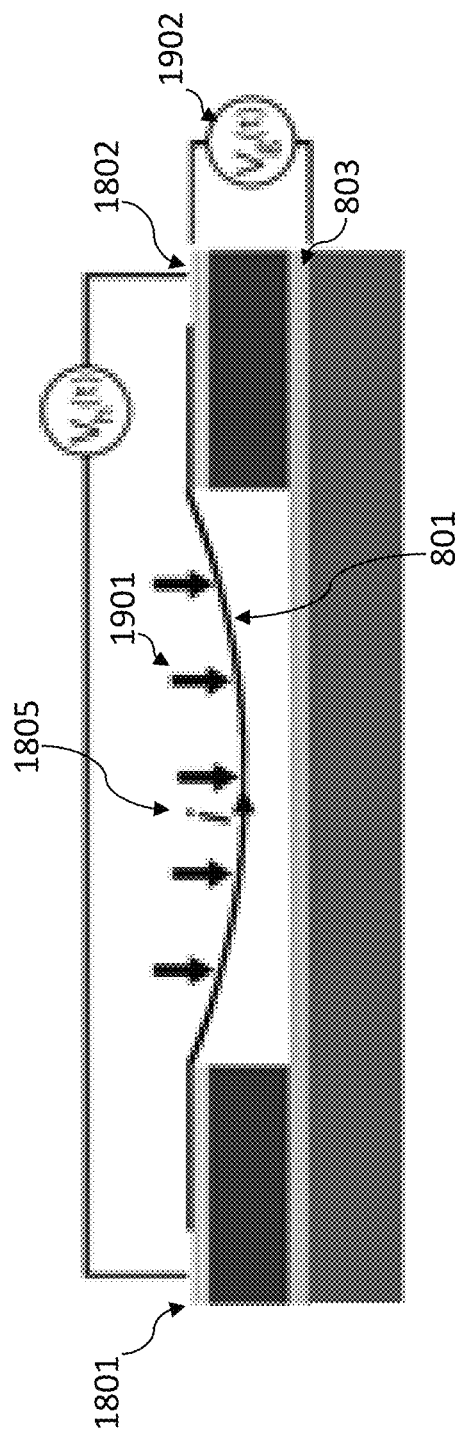


FIG. 19

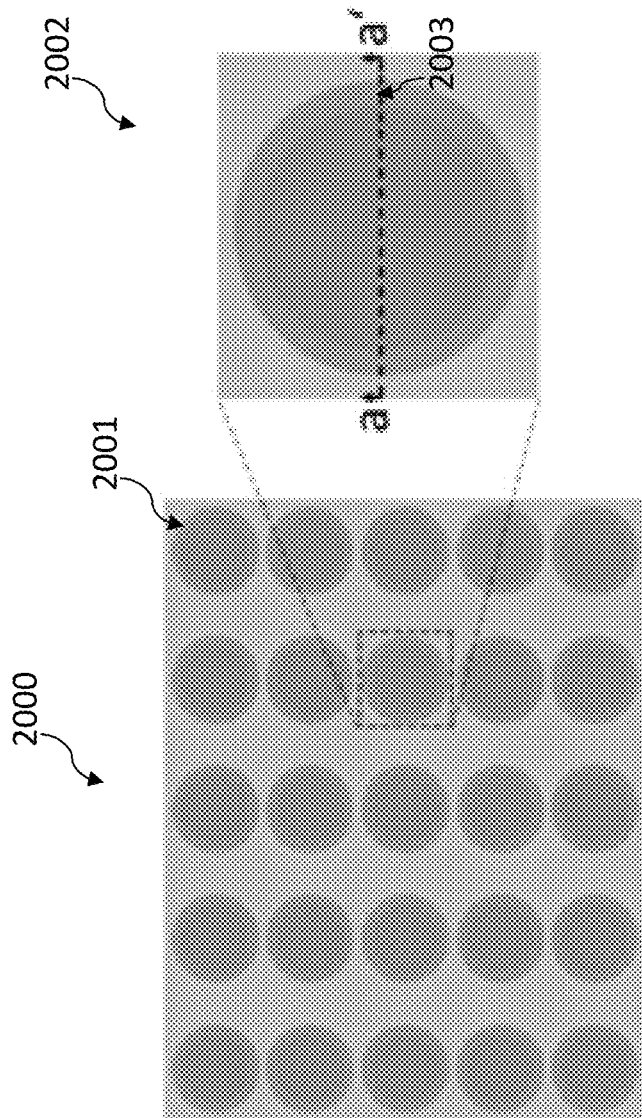


FIG. 20

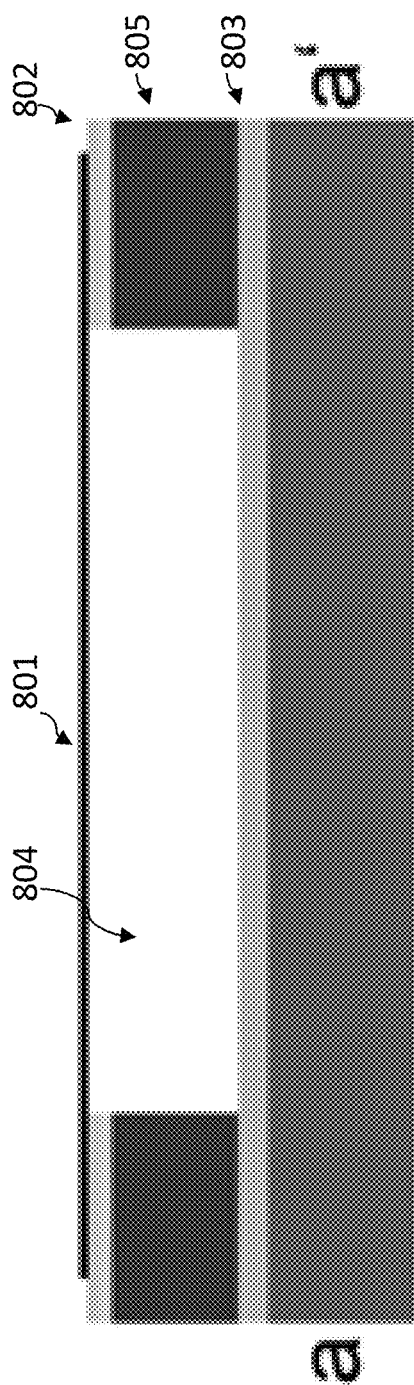
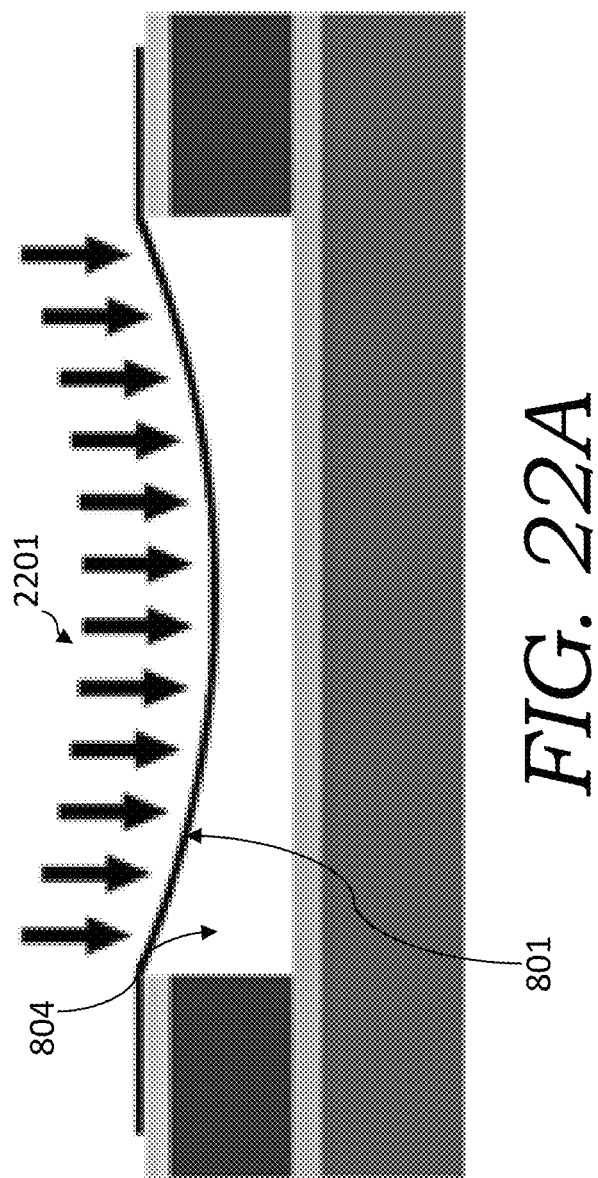
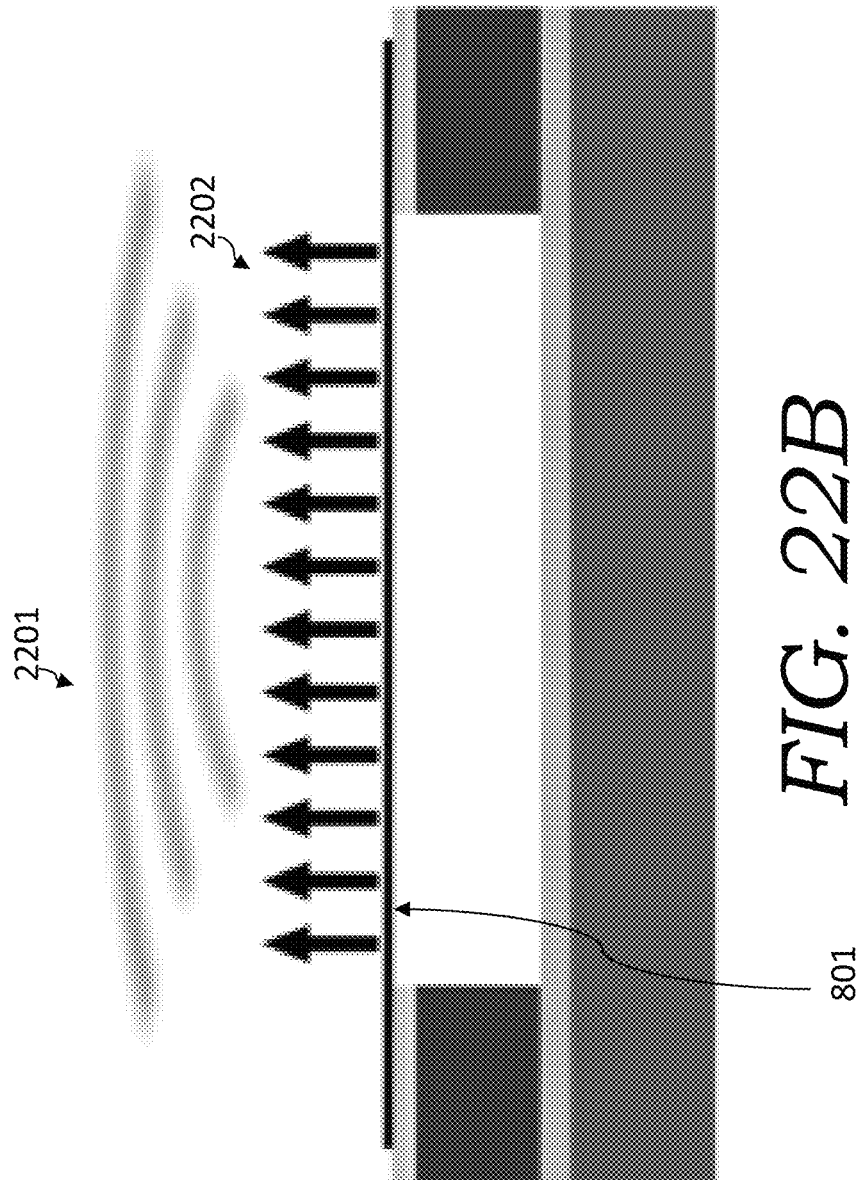


FIG. 21





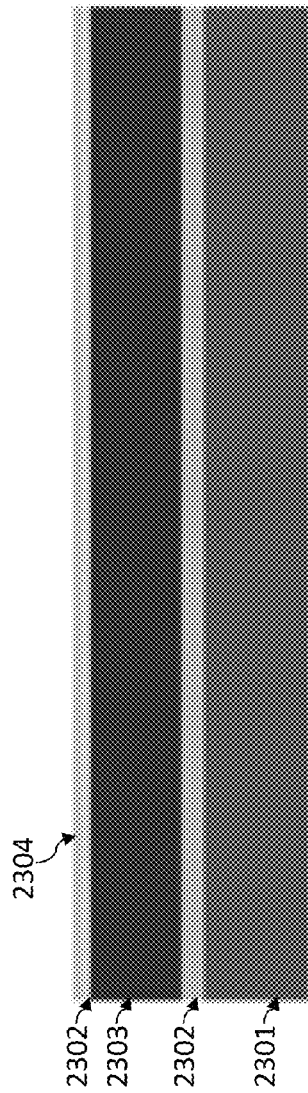


FIG. 23A

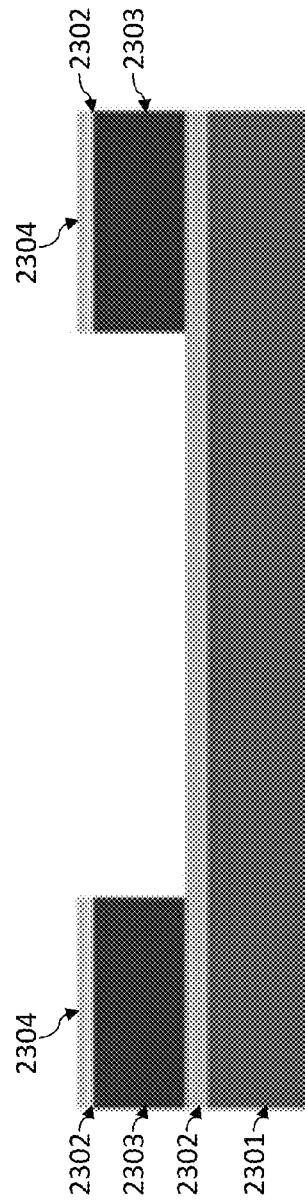


FIG. 23B

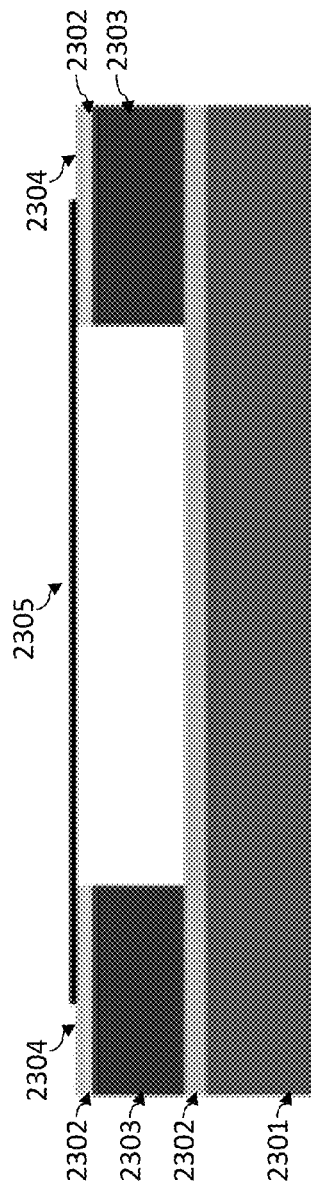


FIG. 23C

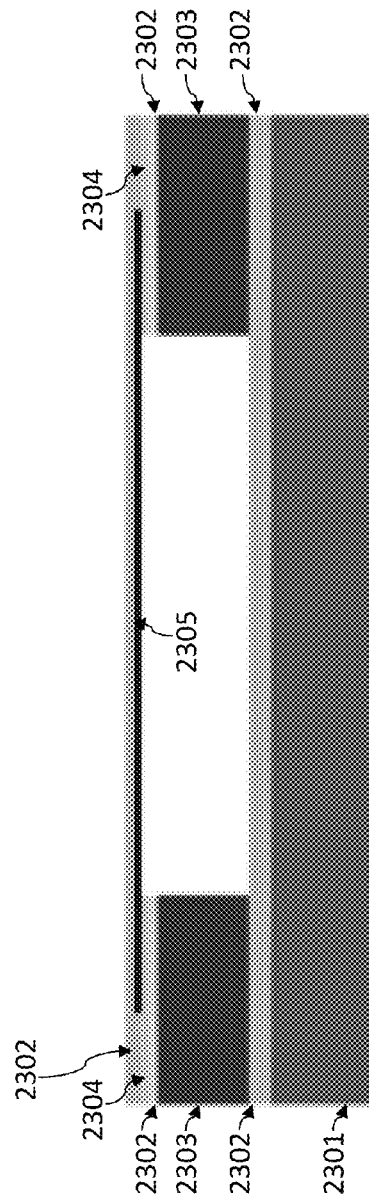


FIG. 23D

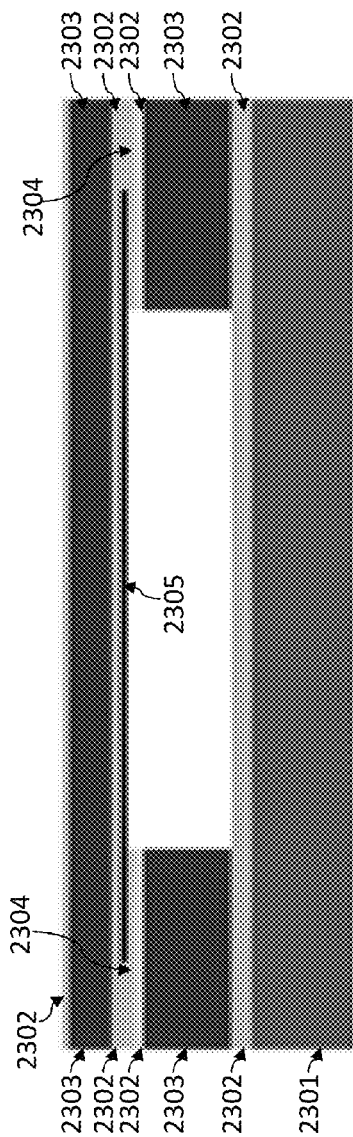


FIG. 23E

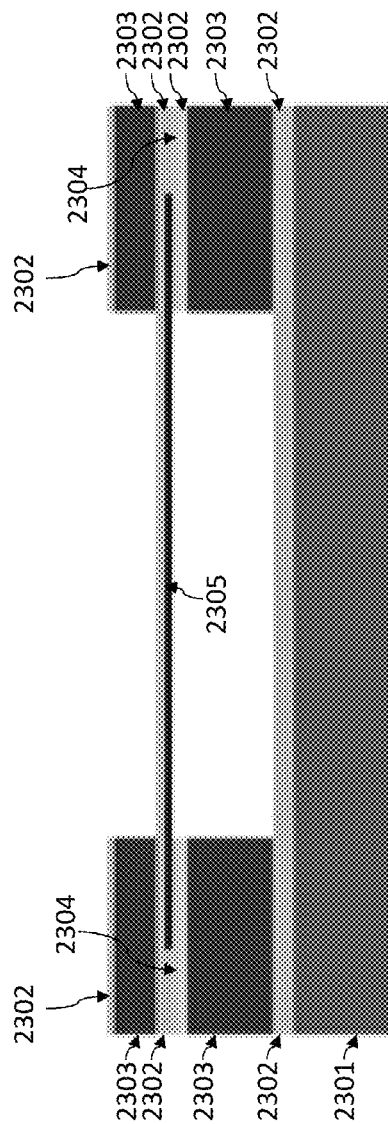


FIG. 23F

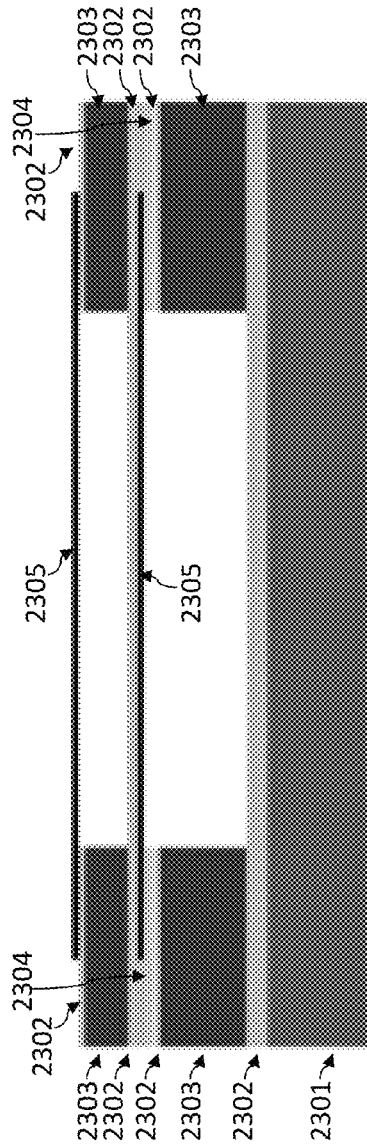


FIG. 23G

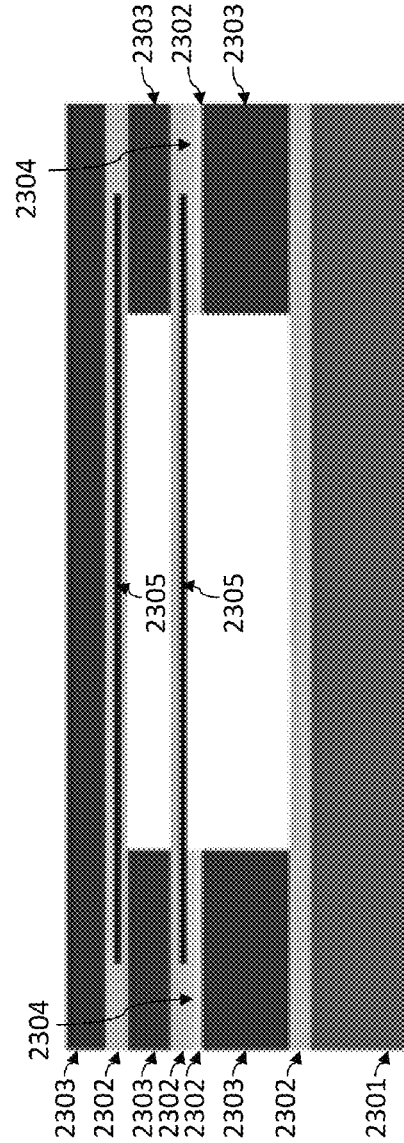


FIG. 23H

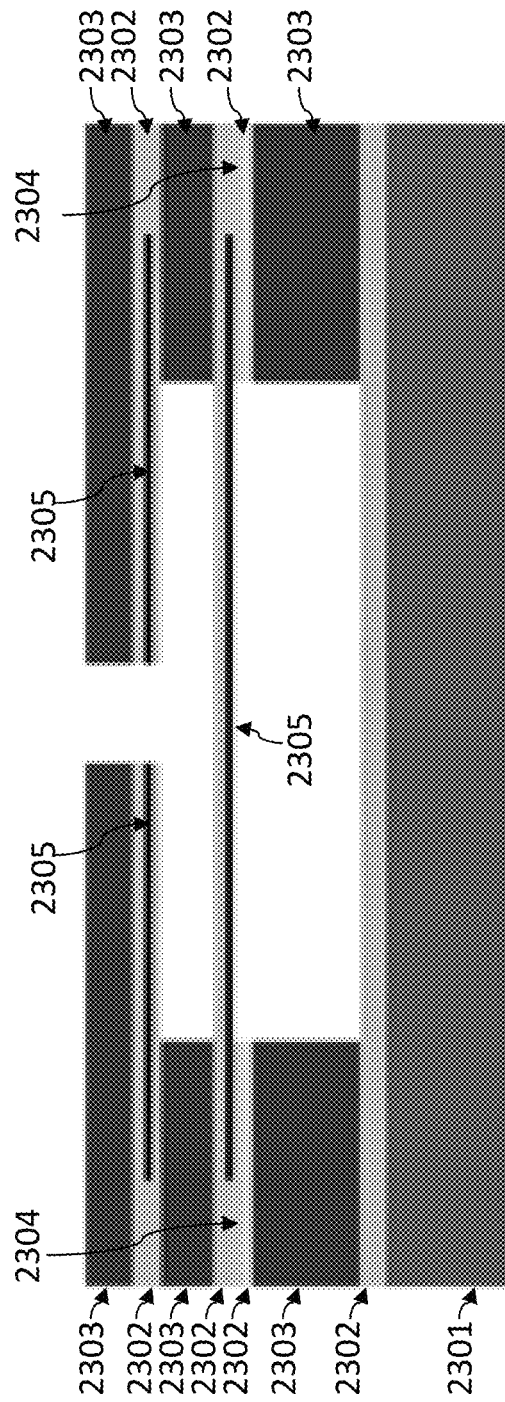


FIG. 23I

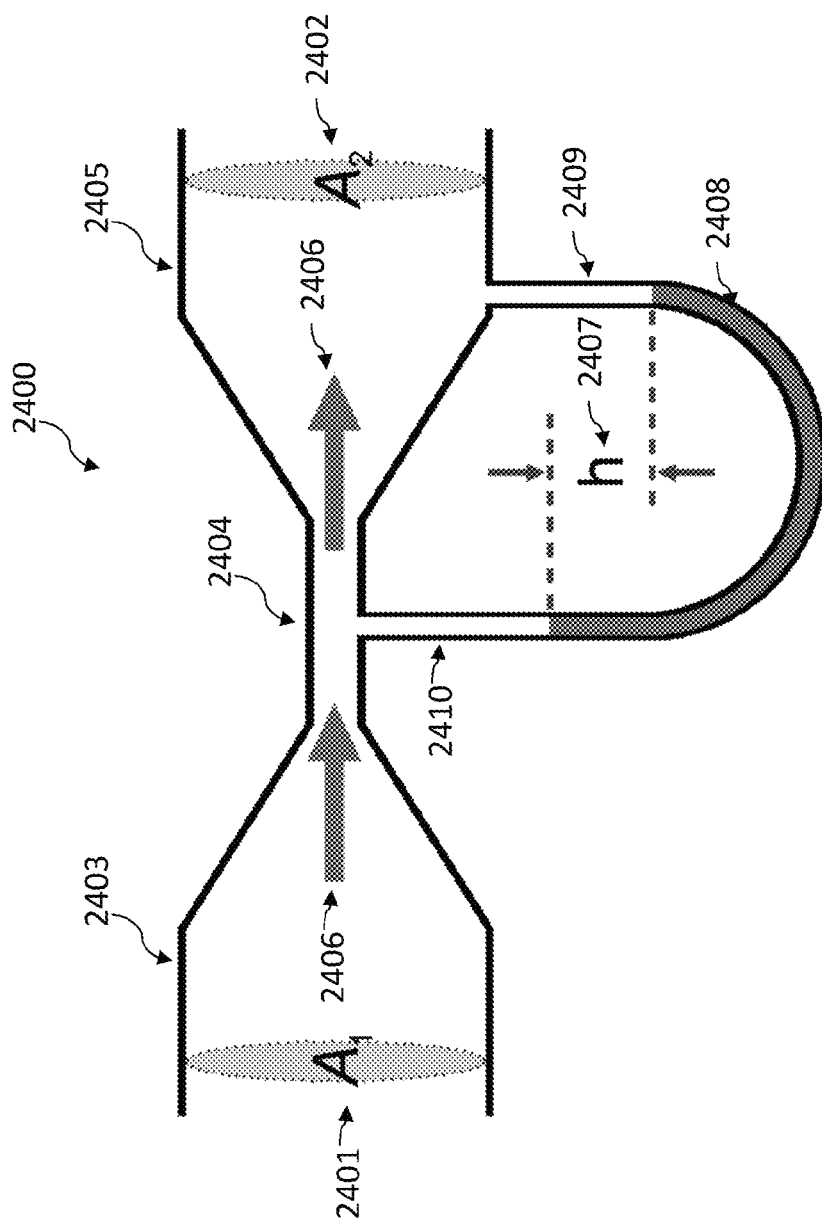


FIG. 24

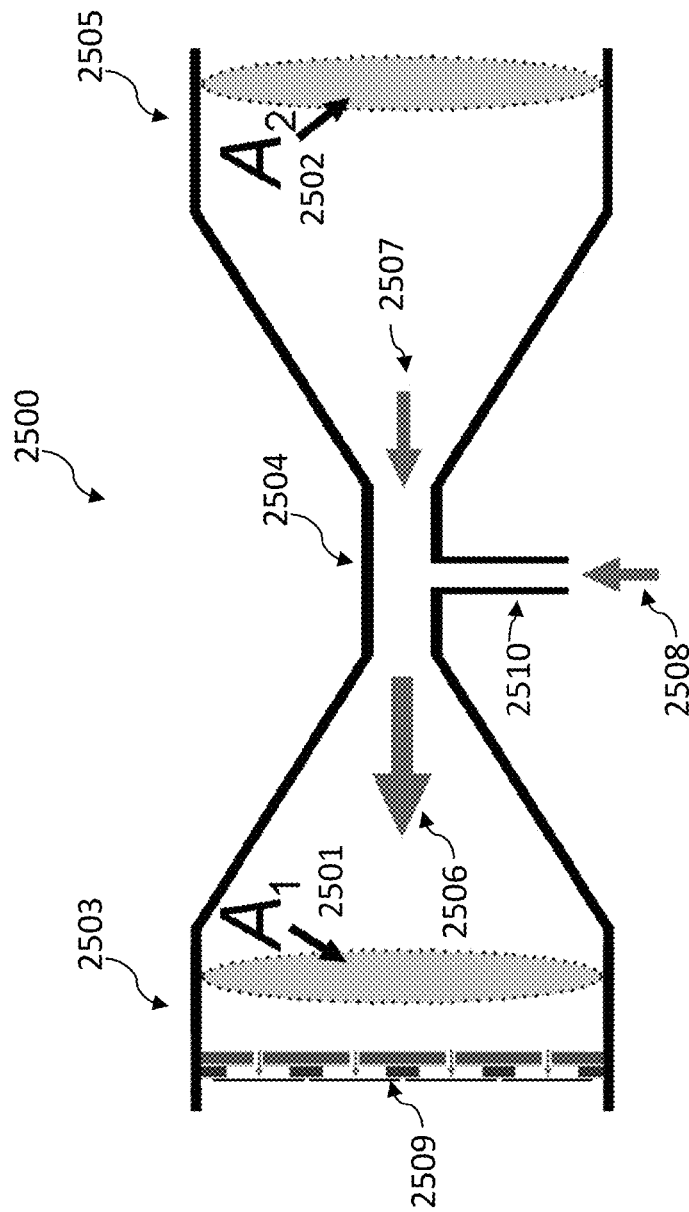


FIG. 25A

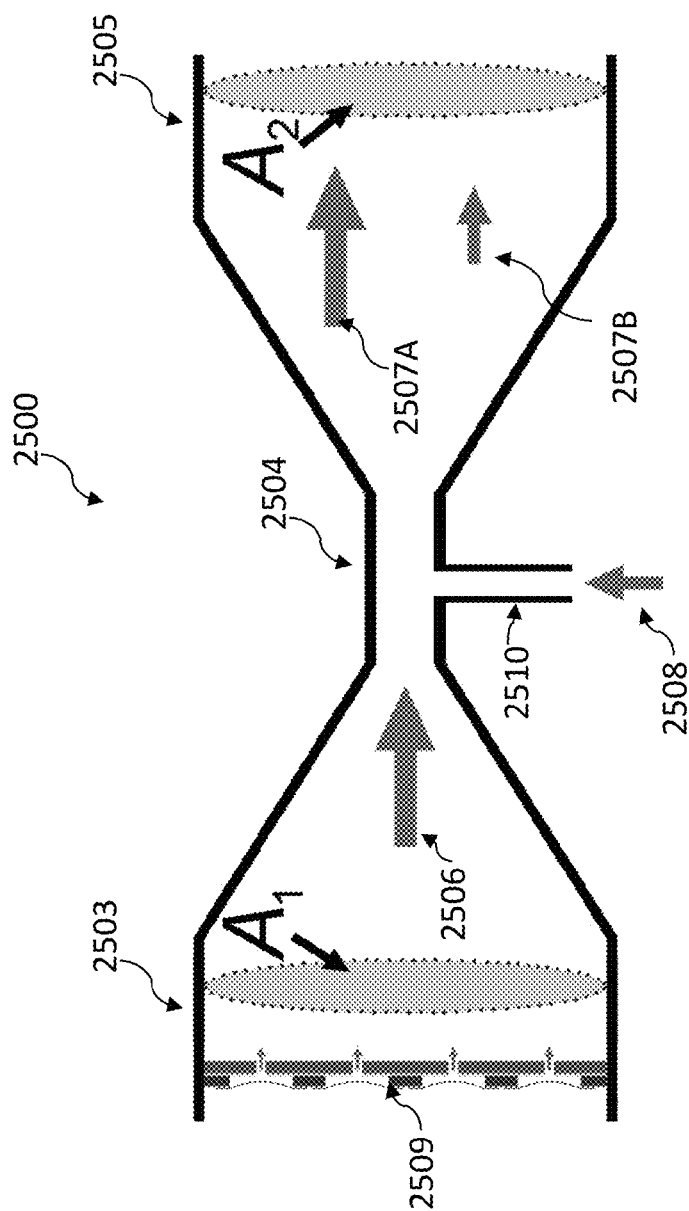


FIG. 25B

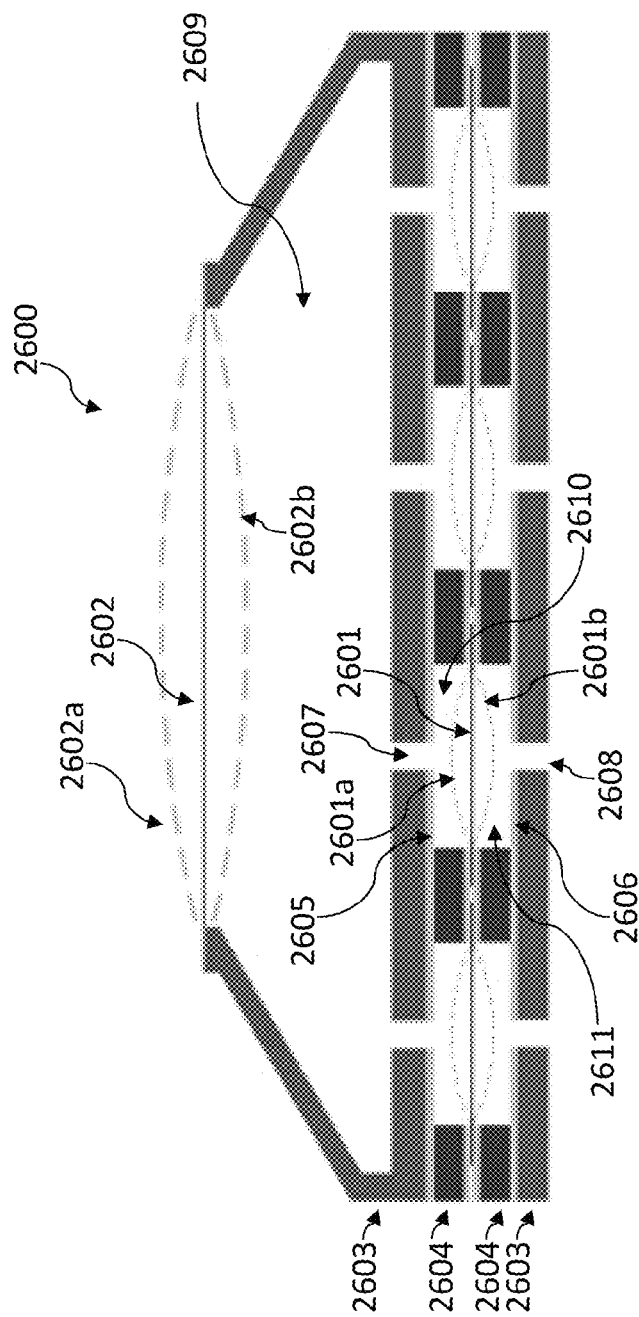


FIG. 26

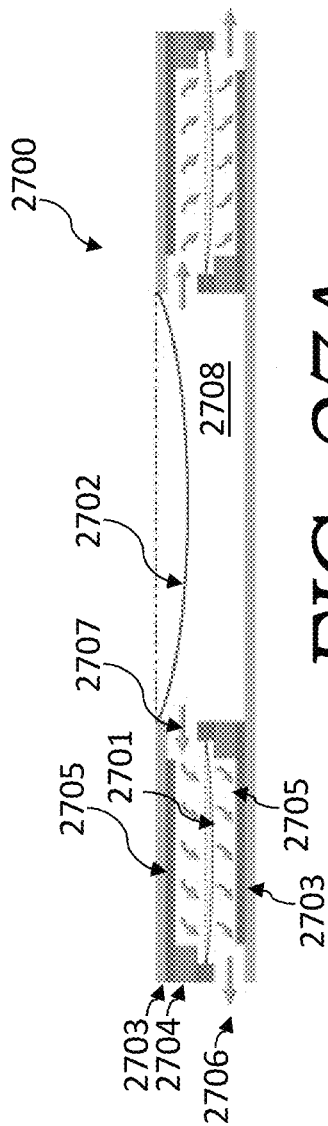


FIG. 27A

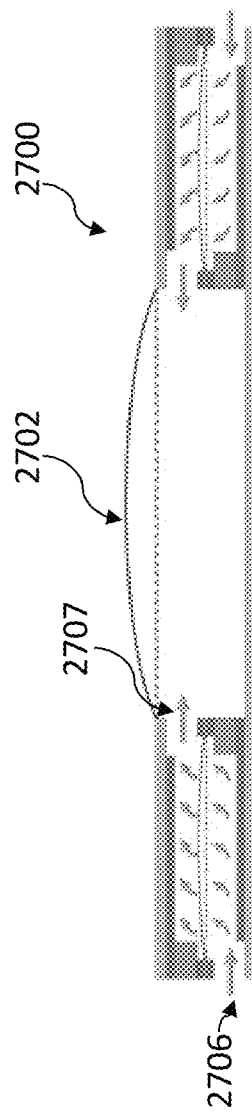


FIG. 27B

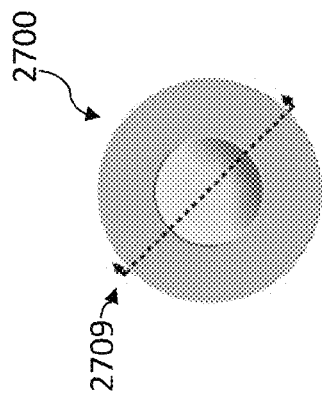


FIG. 27C

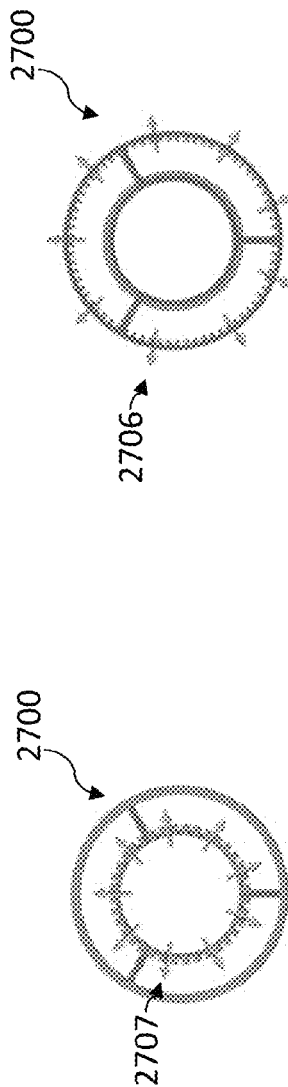


FIG. 27D

FIG. 27E

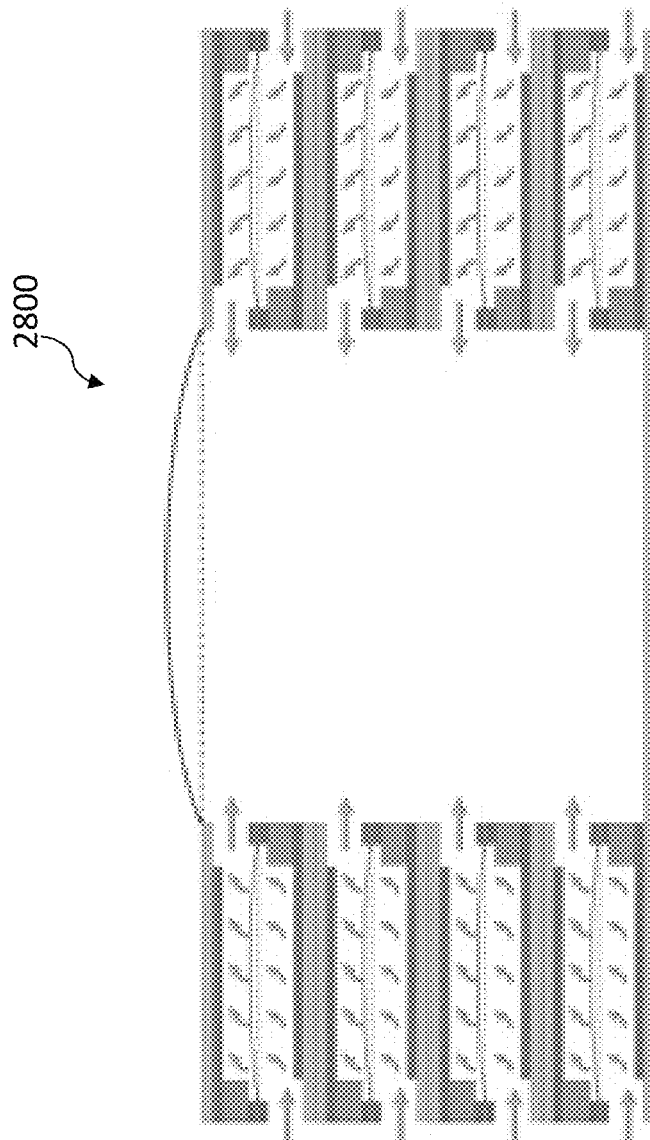


FIG. 28

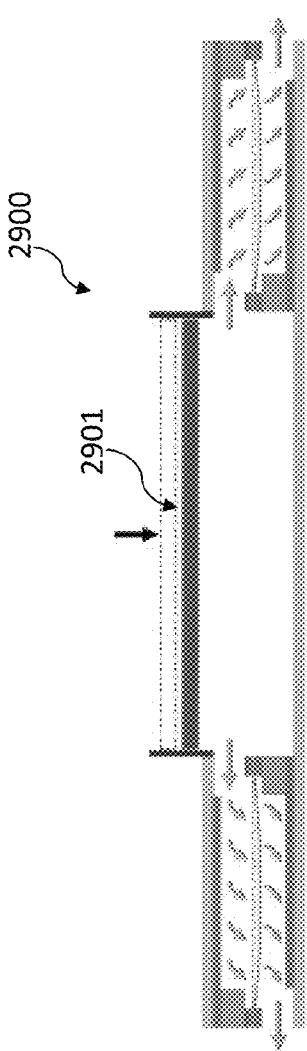


FIG. 29A

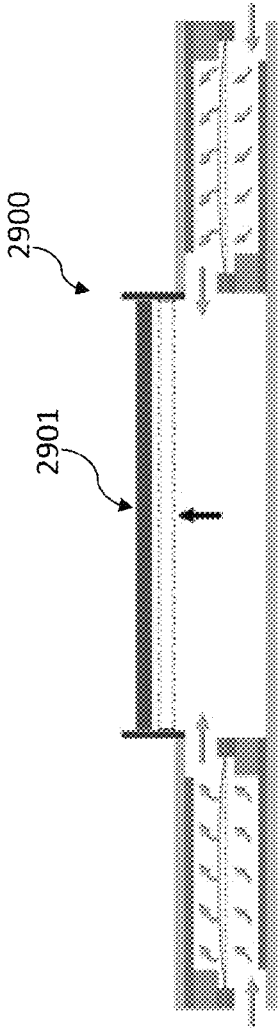


FIG. 29B

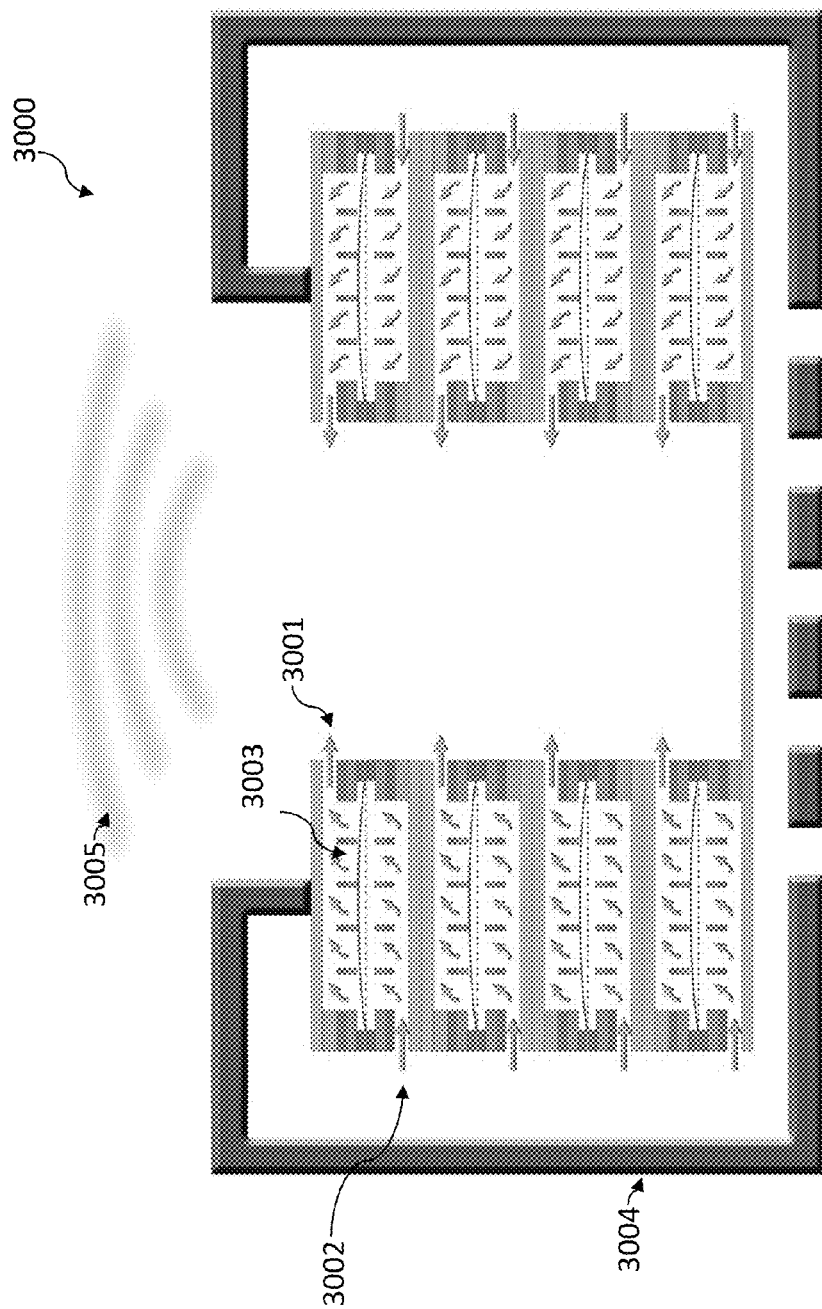


FIG. 30

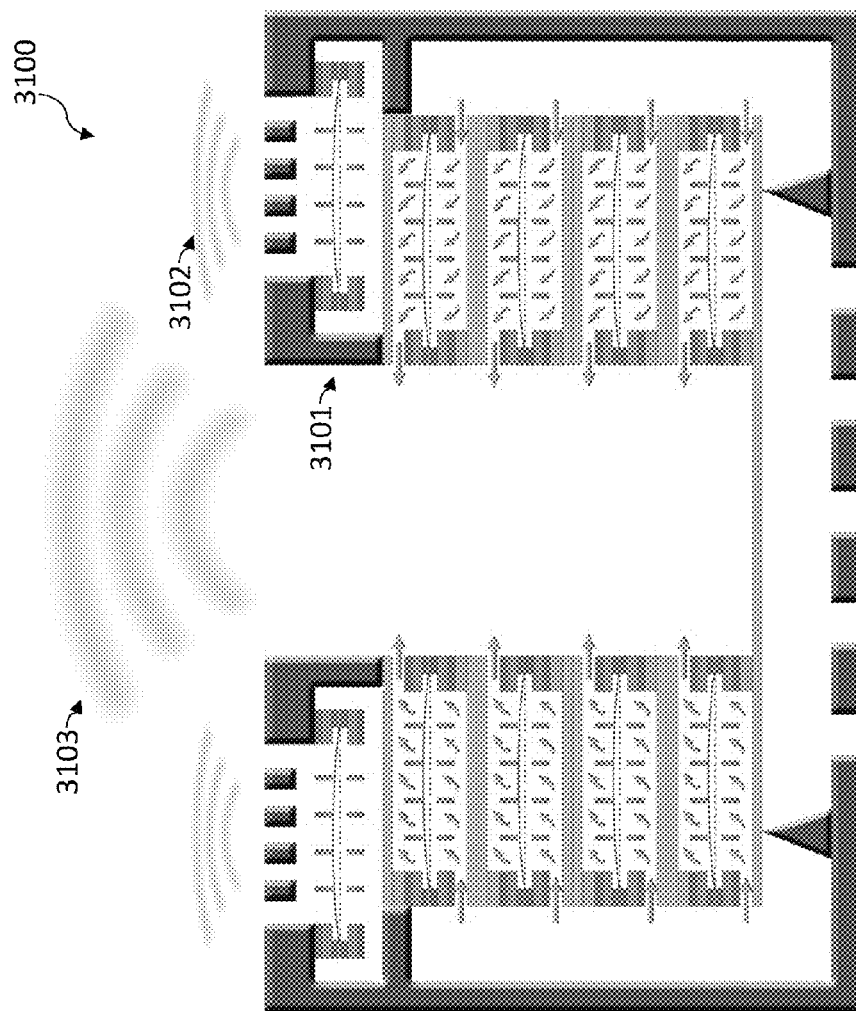


FIG. 31

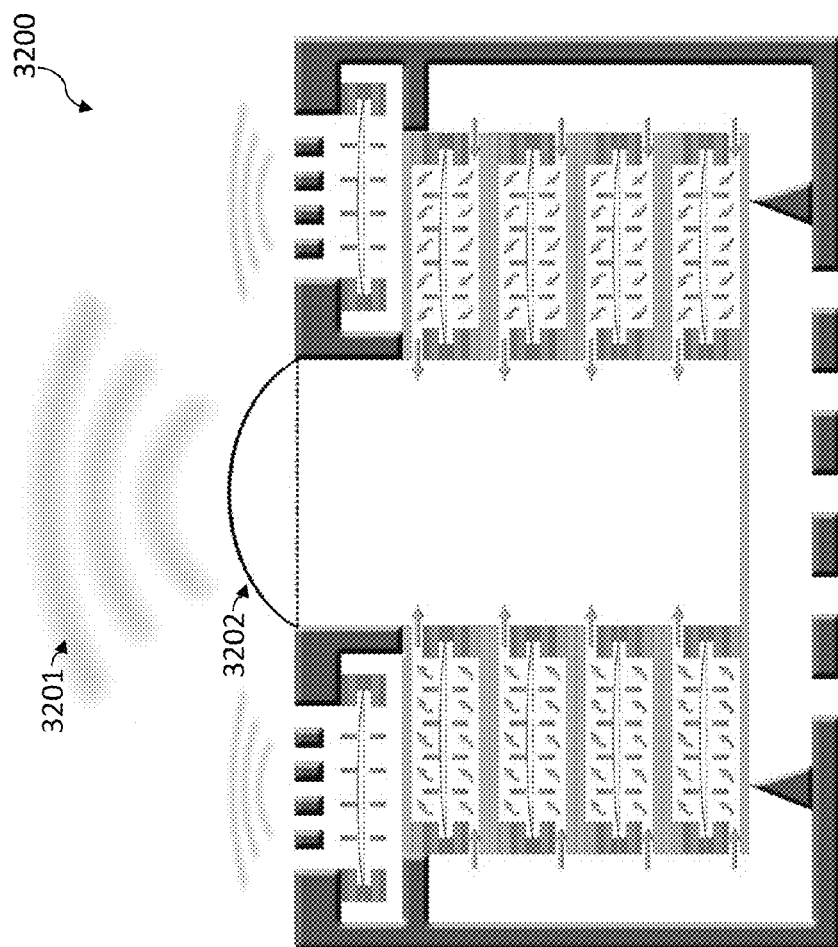


FIG. 32

ELECTRICALLY CONDUCTIVE MEMBRANE PUMP/TRANSDUCER AND METHODS TO MAKE AND USE SAME

RELATED PATENT APPLICATIONS

This application is a continuation-in-part to U.S. Ser. No. 14/161,550 filed on Jan. 22, 2014. This application is also related to U.S. patent application Ser. No. 14/047,813, filed Oct. 7, 2013, which is a continuation-in-part of International Patent Application No. PCT/2012/058247, filed Oct. 1, 2012, which designated the United States and claimed priority to provisional U.S. Patent Application Ser. No. 61/541,779, filed on Sep. 30, 2011. Each of these patent applications is entitled “Electrically Conductive Membrane Transducer And Methods To Make And Use Same.” All of these above-identified patent applications are commonly assigned to the Assignee of the present invention and are hereby incorporated herein by reference in their entirety for all purposes.

TECHNICAL FIELD

The present invention relates to an electrically conductive membrane pump/transducer. The electrically conductive pump transducer includes an array of electrically conductive membrane pumps that combine to generate the desired sound by moving a membrane (such as a membrane of PDMS), a piston, and/or by the use of pressurized airflow in the absence of such a membrane or piston. The electrically conductive membranes in the array can be, for example, graphene-polymer membranes. The electrically conductive pump can include mid-range, tweeter, and sub-woofer speakers.

BACKGROUND

Conventional audio speakers compress/heat and rarify/cool air (thus creating sound waves) using mechanical motion of a cone-shaped membrane at the same frequency as the audio frequency. Most cone speakers convert less than 10% of their electrical input energy into audio energy. These speakers are also bulky in part because large enclosures are used to muffle the sound radiating from the backside of the cone (which is out of phase with the front-facing audio waves). Cone speakers also depend on mechanical resonance; a large “woofer” speaker does not efficiently produce high frequency sounds, and a small “tweeter” speaker does not efficiently produce low frequency sounds.

Thermoacoustic (TA) speakers use heating elements to periodically heat air to produce sound waves. TA speakers do not need large enclosures or depend on mechanical resonance like cone speakers. However, TA speakers are terribly inefficient, converting well under 1% of their electrical input into audio waves.

The present invention relates to an improved transducer (i.e., speaker) that includes an electrically conductive membrane such as, for example, a graphene membrane. In some embodiments, the transducer can be an ultrasonic transducer. An ultrasonic transducer is a device that converts energy into ultrasound (sound waves above the normal range of human hearing). Examples of ultrasound transducers include a piezoelectric transducers that convert electrical energy into sound. Piezoelectric crystals have the property of changing size when a voltage is applied, thus applying an alternating current (AC) across them causes them to oscillate at very high frequencies, thereby producing very high frequency sound waves.

The location at which a transducer focuses the sound can be determined by the active transducer area and shape, the ultrasound frequency, and the sound velocity of the propagation medium. The medium upon which the sound waves are carries can be any gas or liquid (such as air or water, respectively).

Graphene membranes (also otherwise referred to as “graphene drums”) have been manufactured using a process such as disclosed in Lee et al. Science, 2008, 321, 385-388. PCT Patent Appl. No. PCT/US09/59266 (Pinkerton) (the “PCT US09/59266 Application”) described tunneling current switch assemblies having graphene drums (with graphene drums generally having a diameter between about 500 nm and about 1500 nm). PCT Patent Appl. No. PCT/US11/55167 (Pinkerton et al.) and PCT Patent Appl. No. PCT/US11/66497 (Everett et al.) further describe switch assemblies having graphene drums. PCT Patent Appl. No. PCT/US11/23618 (Pinkerton) (the “PCT US11/23618 Application”) described a graphene-drum pump and engine system.

In embodiments of such graphene-drum pump and engine systems the graphene drum could be between about 500 nm and about 1500 nm in diameter (i.e., around one micron in diameter), such that millions of graphene-drum pumps could fit on one square centimeter of a graphene-drum pump system or graphene-drum engine system. In other embodiments, the graphene drum could be between about 10 μ m to about 20 μ m in diameter and have a maximum deflection between about 1 μ m to about 3 μ m (i.e., a maximum deflection that is about 10% of the diameter of the graphene drum). As used herein, “deflection” of the graphene drum is measured relative to the non-deflected graphene drum (i.e., the deflection of a non-deflected graphene drum is zero).

FIG. 1 depicts a perspective view of the graphene-drum pump system illustrated in the PCT US11/23618 Application (described in paragraphs [00102]-[00113] and in FIGS. 1-3, therein). FIGS. 2-3 depict close-ups of the graphene-drum pump (in the graphene-drum pump system of FIG. 1) in exhaust mode and intake mode, respectively.

As illustrated in FIGS. 1-3 (which are similar to FIGS. 1-3 of the PCT US11/23618 Application), the top layer 102 is graphene. The top layer is mounted on an insulating material 103 (such as silicon dioxide). Graphene-drum pump 101 utilizes a graphene drum as the main diaphragm (main diaphragm graphene drum 201). The main diaphragm seals a boundary of the cavity 202 of the graphene-drum pump 101. The cavity is also bounded by insulating material 103 and a metallic gate 203 (which is a metal such as tungsten). The metallic gate 203 is operatively connected to a voltage source (not shown), such as by a metallic trace 204. The main diaphragm graphene drum 201 can be designed to operate in a manner similar to the graphene drums taught and described in the PCT US09/59266 Application and PCT US11/23618 Application.

The graphene-drum pump also includes an upstream valve 205 and a downstream valve 206. As illustrated in FIG. 2, upstream valve 205 includes another graphene drum (the upstream valve graphene drum 207). The upstream valve 205 is connected (a) to a fluid source (not shown) by a conduit 208 and (b) to the cavity 202 by conduit 209, which conduits 208 and 209 are operable to allow fluid (such as a gas or a liquid) to flow from the fluid source through the upstream valve 205 and into the cavity 202. The upstream valve 205 also has a cavity 210 bounded (and sealed) by the upstream valve graphene drum 207, the insulating material 103, and upstream valve gate 211. The upstream valve graphene drum 207 can be designed to operate in a manner similar to the graphene drums taught and described in the PCT US09/

59266 Application and PCT US11/23618 Application. For instance, the upstream valve **205** can be closed or opened by varying the voltage between upstream valve graphene drum **207** and upstream valve gate **211**. When the upstream valve **205** is closed, van der Waals forces will maintain the upstream valve graphene drum **207** in the seated position, which will keep the upstream valve **205** in the closed position.

As illustrated in FIG. 2, the downstream valve **206** includes another graphene drum (the downstream valve graphene drum **212**). The downstream valve **206** is connected (a) to the cavity **202** by a conduit **213** and (b) to a fluid output (not shown) by conduit **214**, which conduits **213** and **214** are operable to allow fluid to flow from the cavity **202** through the downstream valve **206** and into the fluid output. The downstream valve **206** also has a cavity **215** bounded (and sealed) by the downstream valve graphene drum **212**, the insulating material **103**, and downstream valve gate **216**. The downstream valve graphene drum **212** can be designed to operate in a manner similar to the graphene drums taught and described in the PCT US09/59266 Application and PCT US11/23618 Application. For instance, the downstream valve **206** can be closed or opened by varying the voltage between downstream valve graphene drum **212** and downstream valve gate **216**. When the downstream valve **206** is closed, van der Waals forces will maintain the downstream valve graphene drum **212** in the seated position, which will keep the downstream valve **206** in the closed position. Generally, upstream valve gate **211** and downstream valve gate **216** are synchronized so that when the upstream valve **205** is opened, downstream valve is closed (and vice versa).

FIG. 2 depicts the graphene-drum pump **101** in exhaust mode. In the exhaust mode, the upstream valve **205** is closed and the downstream valve **206** is opened, while the main diaphragm graphene drum **201** is being pulled downward (such as due to a voltage between the main diaphragm graphene drum **201** and metallic gate **203**). This results in the fluid (such as air) being pumped from the cavity **202** through the downstream valve **206** and into the fluid output.

FIG. 3 depicts graphene-drum pump **101** in intake mode. In the intake mode, the upstream valve **205** is opened and the downstream valve **206** is closed, while the main diaphragm graphene drum **201** moves upward. (For instance, by reducing the voltage between the main diaphragm graphene drum **201** and metallic gate **203**, the graphene drum **201** will spring upward beyond its “relaxed” position). This results in the fluid (such as air) being drawn from the fluid source through the upstream valve **205** and into the cavity **202**.

To reduce or avoid wear of the upstream valve **205** that utilizes an upstream valve graphene drum **207**, embodiments of the invention can include an upstream valve element **217** to sense the position between the upstream valve graphene drum **207** and bottom of cavity **210**. Likewise to reduce or avoid wear of the downstream valve **206** that utilizes a downstream valve graphene drum **212**, embodiments of the invention can include a downstream valve element **218** to sense the position between the downstream valve graphene drum **212** and bottom of cavity **215**. The reason for this is because of the wear that upstream valve **205** and downstream valve **206** will incur during cyclic operation, which can be on the order of 100 trillion cycles during the device lifetime. Because of such wear, upstream valve graphene drum **207** and downstream valve graphene drum **212** cannot repeatedly hit down upon the channel openings to conduit **209** and conduit **213**, respectively.

As shown in FIG. 2, upstream valve element **217** is shown in the center/bottom of cavity **210** of the upper valve **205**, and downstream valve element **218** is shown in the center/bottom

of cavity **215** of downstream valve **206**. Upstream valve element **217** is used to sense the position of the upstream valve graphene drum **207** relative to the bottom of cavity **210** by using extremely sensitive tunneling currents as feedback. A separate circuit (not shown) is connected between the upstream valve element **217** and the upstream valve graphene drum **207**. Likewise downstream valve element **218** is used to sense the position of the downstream valve graphene drum **212** relative to the bottom of cavity **215** by using extremely sensitive tunneling currents as feedback. A separate circuit (not shown) is connected between the upstream valve element **218** and the upstream valve graphene drum **212**.

With respect to the upstream valve **205**, when the upstream valve graphene drum **207** is within about 1 nm of the upstream valve element **217**, a significant tunneling current will flow between the upstream valve graphene drum **205** and the upstream valve element **217**. This current can be used as feedback to control the voltage of upstream valve gate **211**. When this current is too high, the gate voltage of upstream valve gate **211** will be decreased. And, when this current is too low, the gate voltage of upstream valve gate **211** will be increased (so that the valve stays in its “closed” position, as shown in FIG. 2, until it is instructed to open). There will likely be a gap (around 0.5 nm) between the upstream valve graphene drum **207** and channel opening to conduit **209** when the upstream valve **205** is closed; this gap is so small that it prevents most fluid molecules from passing through the upstream valve **205** yet the gap is large enough to avoid wear. For instance, in an embodiment of the invention, a resistor and voltage source (not shown) can be utilized. The resistor can be placed between the upstream valve element **217** and the voltage source. When the upstream valve graphene drum **207** comes within tunneling current distance (such as around 0.3 to 1 nanometers) of upstream valve element **217**, the tunneling current will flow through upstream valve graphene drum **207**, upstream valve element **217** and the resistor. This tunneling current in combination with the resistor will lower the voltage between upstream valve element **217** and upstream valve graphene drum **207**, thus lowering the electrostatic force between upstream valve element **217** and upstream valve graphene drum **207**. If upstream valve graphene drum **207** moves away from upstream valve graphene drum **217**, the tunneling current will drop and the voltage/force between upstream valve graphene drum **207** and upstream valve element **217** will increase. Thus a 0.3 to 1 nanometer gap between upstream valve graphene drum **207** and upstream valve element **217** is maintained passively which allows the valve to close without causing mechanical wear between upstream valve graphene drum **207** and upstream valve element **217**.

With respect to downstream valve **206**, downstream valve element **218** can be utilized similarly.

In further embodiments, while not shown, standard silicon elements (such as transistors) can be integrated within or near the insulating material **103** near the respective graphene drums (main diaphragm graphene drum **201**, upstream valve graphene drum **207**, or downstream valve graphene drum **212**) to help control the respective graphene drum and gate set.

FIG. 4 depicts another embodiment of a graphene-drum pump system illustrated in the PCT US11/23618 Application (described in paragraphs [00124]-[00127] and in FIG. 7-8, therein). FIG. 5 depicts the graphene-drum pump system of FIG. 4 with the graphene drum in a different position.

In FIGS. 4-5 (which are similar to FIGS. 7-8 of the PCT US11/23618 Application), an alternate embodiment of the present invention is shown that locates the graphene drum **201**

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such that the cavity **202** (in FIG. **2**) is separated into two sealed cavities. (The change of position of graphene drum **201** is shown in FIGS. **4-5**). Per the orientation of FIGS. **4-5**, graphene drum **201** seals an upper cavity **401** and a lower cavity **402**. As shown in FIGS. **4-5**, upstream valve **205** and the downstream valve **206** are positioned to allow the pumping of fluid in and out of upper cavity **401**.

As depicted in FIGS. **4-5**, lower cavity **402** is oriented between the graphene drum **201** and the gate **203**. Lower cavity **402** can be evacuated to increase the breakdown voltage between the graphene drum **201** and the gate **203**. The maximum force (and thus the maximum graphene drum displacement) between the graphene drum **201** and the gate **203** increases as the square of this voltage. Thus, the pumping speed of the device **400** will increase significantly with an increase in the maximum allowable voltage.

As noted above, upper cavity **401** can be filled with air or some other gas/fluid that is being pumped. The vacuum in the lower cavity **402** can be created prior to mounting the graphene drum **201** over the main opening and maintained with a chemical getter. Small channels (not shown) between the lower cavities **402** could be routed to an external vacuum pump to create and maintain the vacuum. A set of dedicated graphene drum pumps mounted in the plurality of graphene drum pumps could also be used to create and maintain vacuum in the lower chambers (since pumping volume is so low these dedicated graphene drum pumps could operate with air in their lower chambers).

Similar to other embodiments shown in the PCT US11/23618 Application, in FIGS. **4-5**, graphene drum **201** can act like a giant spring: i.e., once the gate **203** pulls graphene down (as shown in FIG. **4**), when released the graphene drum **201** will spring upward (as shown in FIG. **5**).

FIG. **6** depicts another embodiment of a graphene-drum pump system illustrated in the PCT US11/23618 Application (described in paragraphs [00129]-[00131] and in FIG. **9**, therein). The graphene-drum pump system **600** shown in FIG. **6** can be actuated without requiring feedback as described above with respect to FIG. **2**. In this embodiment, non-conductive member **604** (such as oxide) is placed between the graphene drum **201** and metallic gate **601** so that the graphene drum **201** cannot go into runaway mode and so that graphene drum **201** will not vigorously impact metallic gate **601** when seating. In embodiments of the invention, setting the graphene drum **201** (non-deflected) to metallic gate **901** distance to 20% of the diameter of the graphene drum **201** will prevent runaway (for a maximum deflection that is in the order of 10% of diameter of the graphene drum **201**) and will allow the graphene drum **201** to seat softly on a surface of the non-conductive member **604** (such as oxide) without the need for feedback.

As shown in FIG. **6**, when the graphene drum **201** is an open position, fluid can flow either (a) in inlet/outlet **602**, through cavity **202**, and out outlet/inlet **603** or (b) in outlet/inlet **603**, through cavity **202**, and out inlet/outlet **902** (due to the pressure differential between inlet/outlet **902** and outlet/inlet **903**).

As shown in FIG. **6**, the metallic gate **601** and metallic trace **605** have a non-conductive member **606** (such as oxide) between them. A voltage source **607** can be placed between the metallic gate **601** and the metallic trace **605** operatively connected to the graphene drum **201**. The non-conductive member **604** physically prevents the graphene drum **201** and the metallic gate **601** from coming in contact with one another. This would prevent potentially damaging impacts of the graphene drum **201** and metallic gate **601**.

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While not illustrated here, in further embodiments of graphene-drum pump systems shown in the PCT US11/23618 Application, such systems can be designed to prevent the graphene drum and metallic gate from coming in contact. For instance, the graphene drum could be located at a distance such that its stiffness precludes the graphene drum from being deflected to the degree necessary for it to come in contact with metallic gate. In such instance, the graphene drum would still need to be located such that it can be in the open position and the closed position. Or, a second and stabilizing system can be included in the embodiment of the invention that is operable for preventing the graphene drum from coming in contact with the gate.

Such embodiments of graphene-drum pump systems illustrated in the PCT US11/23618 Application can be used as a pump to displace fluid. As discussed in the PCT US11/23618 Application, this includes the use of such embodiments in a speaker, such as a compact audio speaker. While the graphene drums operate in the MHz range (i.e., at least about 1 MHz), the graphene drums can produce kHz audio signal by displacing air from one side and pushing it out the other (and then reversing the direction of the flow of fluid at the audio frequency). Utilizing such an approach: (a) provides the ability to make very low and very high pitch sounds with the same and very compact speaker; (b) provides the ability to make high volume sounds with a very small/light speaker chip; and (c) provides a little graphene speaker that would cool itself with high velocity airflow. Accordingly, these graphene-drum pump systems (of PCT US11/23618 Application) solve some of the problems of conventional speakers (such systems are efficient, compact, and can produce sound over the full range of audio frequencies without a loss of sound quality).

However, it has been found that such electrically conductive membrane transducers (of PCT US11/23618 Application) have limitations because these systems require air to flow from the back of the chip/wafer to the front of the chip/wafer. Furthermore, these systems also require the valves to operate properly. Accordingly, there is a need to simplify the design of electrically conductive membrane transducers to reduce their complexity and cost. Furthermore, there is a need to reduce and/or eliminate the contacting and wear of the elements that occurs in these systems of PCT US11/23618 Application.

The two main advantages of the current graphene membrane transducer are that it can draw/push air in/out the same vents (allowing everything to be on one side of the chip/wafer if desired) and the system does not require valves to work. These two simplifications result in much lower complexity and cost. Also, there are no contacting/wear elements in the current invention. Since the graphene membrane transducer sends audio waves out from one face of a chip, there is no need to mount the device in a bulky enclosure (the backside of conventional cone speakers must be sealed to stop oppositely phased sound from canceling front-facing sound). If graphene membrane transducers assemblies are mounted on both sides of a chip, it is also possible to cancel reaction forces (by producing sound waves in phase from each side) and thus unwanted vibration.

SUMMARY OF THE INVENTION

The present invention relates to an electrically conductive membrane transducer. The electrically conductive membrane can be, for example, graphene membrane.

In general, in one aspect, the invention features an audio speaker. The audio speaker includes one or more membrane pumps having an internal vent and an external vent. The

external vent is in fluid communication with atmospheric air. The audio speaker further includes a chamber filled with a gas. The internal vent is in fluid communication with the chamber. The audio speaker further includes a speaker element in fluid communication with the chamber.

Implementations of the invention can include one or more of the following features:

The one or more membrane pumps can be electrostatic membrane pumps.

The one or more membrane pumps can include an electrically conductive membrane.

The electrically conductive membrane can include a polymer and an electrically conductive material.

The electrically conductive material can be graphene.

The electrically conductive material can include a metal.

The polymer can be a polyester membrane.

The audio speaker can further include a first electrically conductive trace below the electrically conductive membrane.

The audio speaker can further include a second electrically conductive trace above the electrically conductive membrane.

The audio speaker can further include an electrically conductive trace above and below the electrically conductive membrane.

The audio speaker can further include a support material. The support material can support the electrically conductive trace. The support material can further support the electrically conductive membrane

At least part of the vent is bounded by the support material.

The support material, the vent, and the electrically conductive trace are made from a printed circuit board.

The electrically conductive membrane has an electrical resistance in excess of one million ohms per square.

The audio speaker wherein the gas is air.

The gas is sulfur hexafluoride

The one or more membrane pumps can include an array of membrane pumps.

The speaker element can be a speaker membrane.

The speaker membrane can include a polymer.

The polymer can be PDMS.

The speaker element can be a speaker piston.

The total surface area of the one or more membrane pumps can be greater than the surface area of the speaker element.

The speaker element and the one or more membrane pumps move at the same frequency.

The average velocity of gas flowing through the internal vent can be higher than the average velocity of gas flowing through the external vent.

The one or more membrane pumps comprise one or more annular membrane pumps.

The one or more annular membrane pumps can include an array of annular membrane pumps.

The array of annular membrane pumps can be stacked about a common axis.

The total area of the annular membrane pumps can be greater than the area of the speaker membrane.

In general, in another aspect, the invention features an audio speaker. The audio speaker includes at least one electrostatic pump that includes an electrically conductive membrane having a first area. The audio speaker further includes an inner vent having a second area. The inner vent is in fluid communication with the electrostatic pump. The audio speaker has an outer vent having a third area. The outer vent is in fluid communication with the electrostatic pump. The first area is at least ten times larger than the second area.

Implementations of the invention can include one or more of the following features:

The first area can be at least 25 times larger than the second area.

The third area is larger than the second area.

The electrically conductive membrane can include a polymer and an electrically conductive material.

The audio speaker can further include a first electrically conductive trace below the electrically conductive membrane.

The audio speaker can further include a second electrically conductive trace above the electrically conductive membrane.

The audio speaker can further include an electrically conductive trace above and below the electrically conductive membrane.

The audio speaker further including a support material. The support material can support the electrically conductive trace. The support material can support the electrically conductive membrane. At least part of the vent can be bounded by the support material. The array of annular electrostatic pumps can be stacked about a common axis.

The audio speaker can further include a chamber having an exhaust area. The total area of the electrostatic pump membranes of the array of annular electrostatic pumps is at least 10 times larger than the exhaust area of the chamber.

The electrically conductive membrane can have has an electrical resistance in excess of one million ohms per square.

The average velocity of air flowing through the inner vent can be higher than the average velocity of air flowing through the outer vent.

In general, in another aspect, the invention features an audio speaker. The audio includes an array of annular membrane pumps having an internal vent and an external vent. The average velocity of air flowing through the internal vent is higher than the average velocity of air flowing through the external vent.

In general, in another aspect, the invention features an audio speaker. The audio speaker includes an electrostatic pump. The audio speaker further includes a vent in fluid communication with the electrostatic pump. The electrostatic pump generates a peak gas pressure within the vent of at least 1 Pa.

Implementations of the invention can include one or more of the following features:

The electrostatic pump can generate a peak gas pressure within the vent of at least 10 Pa.

The gas can be air.

In general, in another aspect, the invention features an audio speaker. The audio speaker includes a plurality of electrostatic pumps. Each of the electrostatic pumps has a vent. The plurality of electrostatic pumps can generate sound in the range between about 20 Hz and about 3000 Hz by flowing air through the vent of the electrostatic pumps.

Implementations of the invention can include one or more of the following features:

The plurality of electronic pumps can include a stack of electronic pumps.

The audio speaker can further include an electrostatic speaker. The electrostatic speaker can generate sound in the range between about 2 KHz and about 20 KHz.

The audio speaker can further include a speaker element in fluid communication with the chamber. The speaker element can be in fluid communication with the electrostatic pumps. The speaker element can moves in response to the flow of air through the vent of the electrostatic pumps. The movement of

the speaker element can generate sound in the range between about 20 Hz and about 200 Hz.

The movement of the speaker element can generate sound in the range below about 100 Hz.

The movement of the speaker element can generate sound in the range below about 80 Hz.

The audio speaker can further include an electrostatic speaker. The electrostatic speaker can generate sound in the range between about 2 KHz and about 20 KHz.

The speaker element can be a speaker membrane.

The speaker membrane can include a polymer.

The polymer can be PDMS.

The speaker element can be a speaker piston.

The plurality of electrostatic pumps can include a first electrostatic pump and a second electrostatic pump. The first electrostatic pump and the second electrostatic pump can be independently controllable. The vent of the first electrostatic pump can have a different cross-sectional area than the vent of the second electrostatic pump. The first electrostatic pump can be operable to produce sound at a first range of frequencies. The second electrostatic pump can be operable to produce sound at a second range of frequencies. The first range of frequencies is not the same range as the second range of frequencies.

The first range of frequencies does not overlap with the second range of frequencies.

DESCRIPTION OF DRAWINGS

FIG. 1 depicts a perspective view of a graphene-drum pump system illustrated in PCT US11/23618 Application.

FIG. 2 depicts a close-up of a graphene-drum pump (in the graphene-drum pump system of FIG. 1) in exhaust mode.

FIG. 3 depicts a close-up of a graphene-drum pump (in the graphene-drum pump system of FIG. 1) in intake mode.

FIG. 4 depicts an alternative embodiment of a graphene-drum pump system.

FIG. 5 depicts the graphene-drum pump system of FIG. 4 with the graphene drum in a different position.

FIG. 6 depicts a further alternative embodiment of a graphene-drum pump system.

FIG. 7 illustrates an array of graphene membrane transducers of the present invention, which includes a magnified illustrated view of one of the graphene membrane transducers.

FIG. 8A depicts a cross-sectional (a-a') illustration of the magnified graphene membrane transducer illustrated in FIG. 7.

FIG. 8B depicts a cross-sectional (b-b') illustration of the magnified graphene membrane transducer illustrated in FIG. 7.

FIG. 8C depicts a cross-sectional (c-c') illustration of the magnified graphene membrane transducer illustrated in FIG. 7.

FIGS. 9A-9C depict an illustration of a graphene membrane transducer (illustrated in FIG. 7) that shows how the graphene membrane moves to cause fluid flow. FIG. 9A illustrates the graphene membrane transducer before an electrostatic forces are applied. FIG. 9B illustrates the graphene membrane transducer when the graphene membrane is being pulled toward the conductive trace due to electrostatic forces. FIG. 9C illustrates the graphene membrane transducer after the electrostatic forces applied in FIG. 9B are reduced or eliminated.

FIG. 10 depicts a normalized graph that shows how the gate voltage, graphene membrane height, and audio power change over a two cycle period in an embodiment of the present invention.

FIG. 11 illustrates an alternative array of graphene membrane transducers of the present invention, which includes a magnified illustrated view of one of the graphene membrane transducers.

FIG. 12 depicts a cross-sectional (a-a') illustration of the magnified graphene membrane transducer illustrated in FIG. 11.

FIGS. 13A-13B depict an illustration of a graphene membrane transducer (illustrated in FIG. 11) that shows how the graphene membrane moves to cause fluid flow. FIG. 13A illustrates the graphene membrane transducer when the graphene membrane is being pulled toward the conductive trace due to electrostatic forces. FIG. 13B illustrates the graphene membrane transducer after the electrostatic forces applied in FIG. 13A are reduced or eliminated.

FIG. 14 illustrates another alternative array of graphene membrane transducers of the present invention, which includes a magnified illustrated view of one of the graphene membrane transducers.

FIG. 15 depicts a cross-sectional (a-a') illustration of the magnified graphene membrane transducer illustrated in FIG. 14.

FIGS. 16A-16B depicts an illustration of a graphene membrane transducer (illustrated in FIG. 14) that shows how the graphene membrane moves to cause fluid flow. FIG. 16A illustrates the graphene membrane transducer when the graphene membrane is being pulled toward the conductive bottom trace due to electrostatic forces. FIG. 16B illustrates the graphene membrane transducer after the electrostatic forces applied in FIG. 16A are reduced or eliminated and when the graphene membrane is being pulled toward the top trace due to electrostatic forces.

FIG. 17 illustrates another alternative array of graphene membrane transducers of the present invention, which includes a magnified illustrated view of two of the graphene membrane transducers.

FIG. 18A depicts a cross-sectional (a-a') illustration of the magnified graphene membrane transducer illustrated in FIG. 17.

FIG. 18B depicts a cross-sectional (b-b') illustration of the magnified graphene membrane transducer illustrated in FIG. 17.

FIG. 19 depicts an illustration of a graphene membrane transducer (illustrated in FIG. 17) that shows how the graphene membrane moves to cause fluid flow.

FIG. 20 illustrates another alternative array of graphene membrane transducers of the present invention, which includes a magnified illustrated view of one of the graphene membrane transducers.

FIG. 21 depicts a cross-sectional (a-a') illustration of the magnified graphene membrane transducer illustrated in FIG. 20.

FIGS. 22A-22B depict an illustration of a graphene membrane transducer (illustrated in FIG. 19) that shows how the graphene membrane moves to cause fluid flow. FIG. 22A illustrates the graphene membrane transducer when the graphene membrane is being pulled toward the conductive trace due to electrostatic forces. FIG. 22B illustrates the graphene membrane transducer after the electrostatic forces applied in FIG. 22A are reduced or eliminated.

FIGS. 23A-23I depict an illustration of a method by which an embodiment of the graphene membrane transducer can be built.

FIG. 24 depicts a system showing a venturi effect.

FIGS. 25A-25B depict illustrations of a graphene membrane pump/transducer that utilizes a venturi channel and that shows how the graphene membranes move to cause fluid flow.

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FIG. 26 depicts an electrically conductive membrane pump/transducer that utilizes an array of electrically conductive membrane pumps that cause a larger membrane to move in phase.

FIGS. 27A-27E depict an electrically conductive membrane pump/transducer that utilizes an array of electrically conductive membrane pumps that cause a membrane to move in phase. FIGS. 27A-27B depict cross-section views of the pump/transducer. FIGS. 27C-27E depict overhead views of the pump/transducer.

FIG. 28 depicts an electrically conductive membrane pump/transducer that has a stacked array of electrically conductive membrane pumps.

FIGS. 29A-29B depict an electrically conductive membrane pump/transducer that utilizes an array of electrically conductive membrane pumps that cause a piston to move in phase.

FIG. 30 depicts an electrically conductive membrane pump/transducer that utilizes an array of electrically conductive membrane pumps that operates without a membrane or piston.

FIG. 31 depicts an electrically conductive membrane pump/transducer 3100 that utilizes an array of electrically conductive membrane pumps and that also includes an electrostatic speaker.

FIG. 32 depicts an electrically conductive membrane pump/transducer 3200 that utilizes an array of electrically conductive membrane pumps that cause a membrane to move in phase and that also includes an electrostatic speaker.

DETAILED DESCRIPTION

The present invention relates to an improved electrically conductive membrane transducer, such as, for example, an improved graphene membrane transducer. The improved electrically conductive membrane transducer does not require air (or other fluid) to flow from the back of the chip/wafer to the front of the chip/wafer. Furthermore, the improved electrically conductive membrane does not require valves to operate. Other advantages of the present invention is that the electrically conductive membrane transducer can draw/push air in/out the same vents (allowing everything to be on one side of the chip/wafer if desired). These simplifications result in much lower complexity and cost.

Also, there is no contacting/wear elements in the current invention.

Moreover, the electrically conductive membrane transducer sends audio waves out from one face of a chip; thus there is no longer any requirement to mount the device in a bulky enclosure (the backside of conventional cone speakers must be sealed to stop oppositely phased sound from canceling front-facing sound).

Furthermore, it is also possible to cancel reaction forces (by producing sound waves in phase from each side) and thus unwanted vibration, by mounting the electrically conductive membrane transducer assemblies on both sides of a chip.

In the preceding and following discussion of the present invention, the electrically conductive membrane of the electrically conductive membrane transducer will be a graphene membrane. However, a person of skill in the art of the present invention will understand that other electrically conductive membranes can be used in place of, or in addition to, graphene membranes (such as in graphene oxide membrane and graphene/graphene oxide membranes).

Referring to the figures, FIG. 7 illustrates an array 700 of graphene membrane transducers 701, which includes a magnified illustrated view 702 of one of the graphene membrane

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transducers 701. Magnified illustrated view 702 provides dotted lines 703, 704, and 705, which define a cross section a-a', b-b', c-c', respectively.

FIG. 8A depicts the cross-sectional (a-a') illustration of the magnified graphene membrane transducer 701 illustrated in FIG. 7. As shown in FIG. 8A, a graphene membrane 801 rests upon and is electrically connected to metallic gate 802. As shown in the orientation of FIG. 8A, the center portion of graphene membrane 801 is above a metallic trace 803 with a cavity 804 between the center of graphene membrane 801 and metallic trace 803. As shown in FIG. 6, the metallic gate 802 and metallic trace 803 have a non-conductive member 805 (such as oxide) between them.

FIG. 8B depicts a cross-sectional (b-b') illustration of the magnified graphene membrane transducer illustrated in FIG. 7.

FIG. 8C depicts a cross-sectional (c-c') illustration of the magnified graphene membrane transducer illustrated in FIG. 7. Per the orientation of FIG. 8C, cavity 804 is in fluid communication with cavity 807 by vented wall 809, and cavity 807 is also bounded by top 806 with vent holes 808. (Per the orientation of FIG. 8C, the vent holes 808 are at the top of cavity 807).

FIGS. 9A-9C depict an illustration of a graphene membrane transducer 701 (illustrated in FIG. 7) that shows how the graphene membrane moves to cause fluid flow. FIG. 9A is the same view as FIG. 8C and illustrates the graphene membrane transducer 701 before an electrostatic forces are applied. As shown in FIG. 9A, the center of graphene membrane 801 is not deflected.

FIG. 9B illustrates the graphene membrane transducer 701 when the graphene membrane 801 is being pulled toward metal trace 803 due to electrostatic forces. In the orientation shown in FIG. 9B, the graphene membrane 801 is being deflected down toward metal trace 803 (as shown by arrows 901). A voltage between the electrically conductive trace 803 and graphene membrane 801 is used to rapidly deflect the graphene membrane 801 downward. This deflection reduces the volume of cavity 804, thereby causing a fluid to flow from cavity 804 to cavity 807 via vented wall 809, as shown by arrow 902. This fluid flow thereby pushes fluid outside cavity 807, via vents 808 of top 806, as shown by arrow 903, which produces waves 904.

In an alternative embodiment, cavity 804 and cavity 807 are not separated by wall 809 (i.e., cavity 804 and cavity 807 are the same cavity).

In a further embodiment, wall 809 is not vented, but rather a membrane that can deflect (i.e., cavity 804 and cavity 807 are isolated from one another). In such instance, when graphene membrane 801 is deflected downward, the increase in pressure inside chamber 804 caused wall 809 to deflect into cavity 807, thereby raising the pressure inside cavity 807. This increased pressure thereby causes fluid to be pushed outside cavity 807, via vents 808 of top 806, as shown by arrow 903, which produces waves 904.

FIG. 9C illustrates the graphene membrane transducer 701 after the electrostatic forces applied in FIG. 9B are reduced or eliminated. When the voltage between the electrically conductive trace 803 and graphene membrane 801 is reduced or eliminated, the graphene membrane 801 will move back to its original position (as shown by arrows 905). When doing so, the decrease in pressure inside cavity 804 (and thereby cavity 807) will allow for the fluid to flow back into cavity 807 and cavity 804, as shown by arrows 906 and 907, respectively. Generally, the rate of this flow back is relatively slow, as compared to the rate at which the fluid flowed out as shown in FIG. 9B.

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FIG. 10 depicts a graph that shows how the gate voltage, graphene membrane height, and audio power change over a two cycle period in an embodiment of the present invention. Gate voltage, graphene membrane height, and audio power are shown in normalized curves 1001, 1002, and 1003, respectively. (These curves have been normalized so that they can be shown on the same graph). The graphene height is the height of the graphene membrane 801 measured relative to the metallic trace 803 (as shown in FIGS. 9A-9C).

The first cycle includes (a) a period 1004 in which in which the gate voltage is rapidly increased, (b) a period 1005 in which the gate voltage is more slowly reduced back to zero, and (c) a period 1006 in which the gate voltage is maintained at zero. The second cycle repeats these periods 1004, 1005, and 1006.

When rapidly increasing the gate voltage during period 1004, the graphene membrane 801 is pulled down rapidly (toward metallic trace 803). When more slowly reducing the gate voltage in period 1005, graphene membrane 801 is let up more slowly. Thus, by shaping the gate voltage appropriately, the rate of movement upward and downward of the graphene membrane is controlled.

Curve 1003 shows how the expelled air power (a combination of the net velocity of the air molecules and the elevated temperature of the expelled air molecules) or audio power is high during the first part of the cycle (peaking at the end of period 1004) and then actually goes negative around a third of the way through the cycle. The reason the air/audio power is negative during the air intake part of the cycle is because the intake air is being cooled as cavity 804 expands. As you can be seen from the relative height of the pulses, the net audio power is positive.

If each of these cycles takes one microsecond, it would take 500 of these cycles to build up the high pressure part of a 1 kHz audio wave. The graphene membrane transducer array (such as array 700) may be driven harder during certain parts of the 500 cycles (and some graphene membrane transducers may be out of phase with other graphene membrane transducers) to better approximate a smooth audio wave.

FIG. 11 illustrates an array 1100 of alternative graphene membrane transducers 1101, which includes a magnified illustrated view 1102 of one of the graphene membrane transducers 1101. Magnified illustrated view 1102 provides dotted line 1103, which defines a cross section a-a'.

FIG. 12 depicts the cross-sectional (a-a') illustration of the magnified graphene membrane transducer 1101 illustrated in FIG. 11. Similar to graphene membrane transducer 701, graphene membrane transducer 1101 has graphene membrane 801, metallic gate 802, metallic trace 803, cavity 804, and non-conductive member 805. As shown in FIG. 12, graphene membrane transducer 1101 also has a vent hole 1201 through which fluid may flow out of cavity 804. By this arrangement of vent hole 1201, the density of graphene membrane transducers 1101 can be increased in array 1100 (as compared to the density of graphene membrane transducers 701 in array 700).

FIG. 13A illustrates the graphene membrane transducer 1101 when the graphene membrane 801 is being pulled toward metal trace 803 due to electrostatic forces. In the orientation shown in FIG. 13A, the graphene membrane 801 is being deflected down toward metal trace 803 (as shown by arrows 1301). As with graphene membrane transducer 701, a voltage between the electrically conductive trace 803 and graphene membrane 801 is used to rapidly deflection the graphene membrane 801 downward. This deflection reduces the volume of cavity 804, thereby causing a fluid to flow out

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of cavity 804 through vent hole 1201, as shown by arrow 1302, which produces waves 1303.

FIG. 13B illustrates the graphene membrane transducer 1001 after the electrostatic forces applied in FIG. 13A are reduced or eliminated. When the voltage between the electrically conductive trace 803 and graphene membrane 801 is reduced or eliminated, the graphene membrane 801 will move back to its original position (as shown by arrows 1305). When doing so, the decrease in pressure inside cavity 804 will allow for the fluid to flow back into cavity 804, as shown by arrow 1304. Similar to graphene membrane transducer 701, generally, the rate of this flow back is relatively slow, as compared to the rate at which the fluid flowed out as shown in FIG. 13A.

FIG. 14 illustrates an array 1400 of alternative graphene membrane transducers 1401, which includes a magnified illustrated view 1402 of one of the graphene membrane transducers 1401. Magnified illustrated view 1402 provides dotted line 1403, which defines a cross section a-a'.

FIG. 15 depicts the cross-sectional (a-a') illustration of the magnified graphene membrane transducer 1401 illustrated in FIG. 14. Similar to graphene membrane transducer 701 and graphene membrane transducer 1101, graphene membrane transducer 1401 has graphene membrane 801, metallic gate 802, metallic trace 803, cavity 804, and non-conductive member 805. As shown in FIG. 15, graphene membrane transducer 1401 also has a cavity 1501 and a vent hole 1502 through which fluid may flow out of cavity 1501. Furthermore, graphene membrane transducer 1401 also a second metallic trace 1503 with a non-conductive member 1504 (such as oxide) between them.

FIG. 16A illustrates the graphene membrane transducer 1401 when the graphene membrane 801 is being pulled toward metal trace 803 due to electrostatic forces. In the orientation shown in FIG. 16A, the graphene membrane 801 is being deflected down toward metal trace 803 (as shown by arrows 1601). As with graphene membrane transducer 701, a voltage between the electrically conductive trace 803 and graphene membrane 801 is used to deflect the graphene membrane 801 downward. If V_2 is set to ground, this deflection is caused by increasing the voltage at V_3 . This deflection reduces the volume of cavity 804 (increasing the pressure inside cavity 804) and increases the volume of cavity 1501, thereby causing a fluid to flow into cavity 1501 through vent hole 1502, as shown by arrow 1502.

FIG. 16B illustrates the graphene membrane transducer 1401 after the electrostatic forces applied in FIG. 16A are reduced or eliminated and when the graphene membrane 801 deflected back toward the second metallic trace 1503 due to electrostatic forces. When the voltage between the electrically conductive trace 803 and graphene membrane 801 is reduced or eliminated (such as by reducing the voltage at V_3) and the voltage between second metallic trace 1503 and graphene membrane 801 is increased (such as by increasing the voltage at V_1) the graphene membrane 801 will deflect back toward the second metallic trace 1503 (as shown by arrows 1603). When doing so, the increase in pressure inside cavity 1501 will cause to flow out of cavity 1501 through vent hole 1502, as shown by arrow 1604, which produces waves 1605.

Typically, a gas is maintained in cavity 804, which is sealed. Since the gas in cavity 804 is compressed beneath the graphene membrane 801 as fluid is drawn in the vent hole 1502 (as shown in FIG. 16A), per the orientation of FIGS. 16A-16B, this produces an upward pressure on the graphene membrane 801 that can help push the fluid out of the vent hole 1502 during the exhaust phase shown in FIG. 16B. The

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mechanical restoration force of the graphene membrane **801** also aids in pushing fluid out the vent hole **1502** along with the electrostatic force between the graphene membrane **801** and the second metallic trace **1503**.

Graphene membrane transducer **1401** is also capable of cooling the fluid (such as air) if the graphene membrane **801** is pulled down rapidly (as shown in FIG. **16A**) and raised slowly back up toward the vent hole (as shown in FIG. **16B**). In this embodiment the graphene membrane transducer could thus be used to create the low density or cool portion of a sound wave or just be used for cooling in general.

Calculations show the ratio of graphene membrane area to vent area should be about ten to about 100 and the mechanical frequency of the graphene membrane should be on the order of 1 MHz for a 25 μ diameter graphene drum.

The main operating principle is that air (or other fluid) is drawn in slowly and pushed out quickly (push out time is about three times to about ten times faster than the draw in time). To make a 1 kHz audio signal, an array (thousands to millions) of graphene membrane transducers should cycle about 500 times for each positive portion of the audio wave at on the order of 1 MHz. A cycle includes drawing in air or other fluid and pushing the air or other fluid out over a period of time. For example, a cycle could include drawing in air or other fluid for about 850 ns and pushing the air or other fluid out for about 150 ns over a half a millisecond period to produce the high pressure part of audio wave and then not pumping for another half a millisecond to "produce" the low pressure part of sound wave.

Although the 1 MHz component of the wave is contained within lower frequency audio wave, it cannot be perceived by the human ear. Thus, in some embodiments, the transducer can be an ultrasonic transducer. However, when needed, groups of graphene membrane transducers can be pumped out of phase from each other to cancel the MHz component of the audio wave, thus yielding waves audible to the human ear.

Furthermore, if desired, embodiments of the present invention can be optically transparent and flexible. For example, the primary substrate could be glass in place of silicon and the metal traces could be made of graphene. Mounting speakers on top of display screens may be attractive in some applications (like cell phone, computer and TV screens). The reaction force of the graphene membrane transducers can also be used to levitate and position the graphene membrane transducer array (i.e., the speakers could be directed to position themselves in three dimensions within a room or outdoor arena).

FIG. **17** illustrates another alternative array **1700** of graphene membrane transducers of the present invention, which includes a magnified illustrated view of two of the graphene membrane transducers **1701**. Magnified illustrated view **1702** provides dotted lines **1703** and **1704**, which define a cross section a-a' and b-b', respectively.

FIGS. **18A-18B** depict cross-sectional illustrations (a-a' and b-b', respectively) of the magnified graphene membrane transducer **1701** illustrated in FIG. **17**. Similar to graphene membrane transducer **701**, graphene membrane transducer **1101**, and graphene membrane transducer **1401**, graphene membrane transducer **1701** has graphene membrane **801**, metallic trace **803**, cavity **804**, and non-conductive member **805**. In this embodiment, graphene membrane **801** spans two conductive traces (trace **1801** and trace **1802**, which can be metallic traces). The space between trace **1801** and trace **1802** forms two vents. One of these vents (vent **1803**) is shown in FIG. **18B**. The other vent is not shown in FIG. **18B**, as it is on the opposing side of graphene membrane transducer **1701**.

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By placing a voltage **1804** across trace **1801** and trace **1802**, current **1805** (generally in the kHz range and in a range closely related to the desired audio signal) can be applied from one trace (trace **1801**), through the graphene membrane **801**, and into the other trace (trace **1802**), which will heat the graphene membrane **801** (via resistance heating). In graphene membrane transducer **1701**, the majority of current **1805** will run across the vent **1803** and the other vent because this is the path of least resistance (and where most of the resistive heating will take place).

FIG. **19** illustrates the graphene membrane transducer **1701** when the graphene membrane **801** is being pulled toward metal trace **803** (as shown by arrows **1901**) due to electrostatic forces (i.e., by placing a voltage **1902** between graphene **801** and metallic trace **803**). Such voltage **1901** can have a frequency in the MHz range, which will make the graphene membrane transducer **1701** pump air in and out of vent **1803** and the other in the order of 100 m/s (which will remove the heat from the graphene membrane **801** and impart it to the surrounding air).

Accordingly, metallic trace **803** can be used to make the graphene membrane **801** oscillate (such as in the MHz range), which will force cooling air across the graphene membrane **801** (and will heats this airflow). Such a system can be used to enhance the transducer mode of the present invention or can be used in a thermo-acoustic mode of the present invention.

FIG. **20** illustrates an array **2000** of another alternative graphene membrane transducers **2001**, which includes a magnified illustrated view **2002** of one of the graphene membrane transducers **2001**. Magnified illustrated view **2002** provides dotted line **2003**, which defines a cross section a-a'.

FIG. **21** depicts the cross-sectional (a-a') illustration of the magnified graphene membrane transducer **2001** illustrated in FIG. **17**. Similar to graphene membrane transducer **701**, graphene membrane transducer **1101**, and graphene membrane transducer **1401**, graphene membrane transducer **2001** has graphene membrane **801**, metallic gate **802**, metallic trace **803**, cavity **804**, and non-conductive member **805**. As shown in FIG. **21**, graphene membrane transducer **2001** is similar to graphene membrane **1101** except that it does not have a vent hole **1201**.

FIG. **22A** illustrates the graphene membrane transducer **2001** when the graphene membrane **801** is being pulled toward metal trace **803** due to electrostatic forces. In the orientation shown in FIG. **22A**, the graphene membrane **801** is being deflected down toward metal trace **803** (as shown by arrows **2201**). As with graphene membrane transducer **1101**, a voltage between the electrically conductive trace **803** and graphene membrane **801** is used to deflect the graphene membrane **801** downward. This deflection reduces the volume of cavity **804**, thereby increasing the pressure inside cavity **804**, which is sealed and filled with a gas.

FIG. **22B** illustrates the graphene membrane transducer **2001** after the electrostatic forces applied in FIG. **22A** are reduced or eliminated. When the voltage between the electrically conductive trace **803** and graphene membrane **801** is reduced or eliminated, the graphene membrane **801** will move back to its original position (as shown by arrows **2202**).

As discussed above, a gas is maintained in cavity **804**, which is sealed. Since the gas in cavity **804** is compressed beneath the graphene membrane **801** as (as shown in FIG. **22A**), per the orientation of FIGS. **22A-22B**, this produces an upward pressure on the graphene membrane **801** that can will push the fluid up as during the phase shown in FIG. **22B** (as shown by waves **2201**).

This system can replace piezoelectric transducers used in conventional liquid ultrasonic applications such as medical

imaging. Graphene membrane **801** can be made of several layers of graphene to insure that a water-tight seal is maintained between the graphene and cavity **804**.

This system can produce ultrasonic waves at a frequency equal to the mechanical frequency of the graphene membranes.

A significant advantage over prior art ultrasonic transducers is that the present invention has the ability to operate over a wide range of frequencies without losing efficiency. Moreover, the system of the present invention does not need to operate in mechanical resonance, which is often the case with piezoelectric ultrasonic transducers.

Moreover, if some electrically conductive particles are deposited on the electrically conductive trace **803**, field emission current between the moveable graphene and these trace particles can be used to sense ultrasonic vibrations in a fluid or gas (i.e., graphene membrane **801** will oscillate in response to pressure changes and these mechanical oscillations will cause a field emission or tunneling currents to oscillate at this same frequency).

FIGS. **23A-23I** depict an illustration of a method by which an embodiment of the graphene membrane transducer can be built. It should be noted that FIGS. **23A-23I** show how graphene can be used as scaffolding to build up layered devices (containing voids) without using problematic/expensive chemical mechanical polishing. Although the process shown in the figures is used to build a graphene membrane transducer (in this case graphene membrane transducer **1301** as shown in FIG. **14**), this process is generally applicable to any MEMS/NEMS device that requires one or more layers with voids.

As illustrated in FIGS. **23A-23I**, material **2301** can be silicon or glass, material **2302** is a metal (like tungsten), material **2303** is an electrical insulator (like oxide), the material **2304** is a metal (like gold), and the material **2305** is graphene.

FIG. **23A** illustrates a layered substrate from top to bottom of gold **2304**, tungsten **2302**, oxide **2303**, tungsten **2302**, and silicon **2301**.

FIG. **23B** illustrates a layered substrate in which portions of the top layers of gold **2304**, tungsten **2302**, oxide **2303** were removed by techniques known in the art. The exposed layer of tungsten that has not been removed is metal trace **803** of graphene membrane transducer **1301**. Moreover, the portion of oxide **2303** that remains is non-conductive member **805** of graphene membrane transducer **1301**.

FIG. **23C** illustrates the positioning of a graphene membrane **2305** on top of the layered substrate shown in FIG. **23B**. Techniques to transfer and position graphene membranes over target features are disclosed and taught in pending and co-owned U.S. patent application Ser. No. 13/098,101 (Lackowski et al.) and 61/427,011 (Everett et al.). This graphene membrane is the graphene membrane **801** of graphene membrane transducer **1301**. Moreover, the cavity formed below graphene membrane **2305** in FIG. **23C** is cavity **804** of graphene membrane transducer **1301**.

FIG. **23D** illustrates depositing tungsten **2302** on top of graphene membrane **2305** using techniques known in the art. The combination of the tungsten **2305** and gold **2304** about the graphene membrane is the metallic gate **802** of graphene membrane transducer **1301**.

FIG. **23E** illustrates depositing oxide **2303** and then depositing tungsten **2302** on top of the oxide **2303** using techniques known in the art.

FIG. **23F** illustrates the layered substrate in which portions of the top layers of tungsten **2302** and oxide **2303** were removed by techniques known in the art. The portion of oxide

2303 that remains is non-conductive member **1404** of graphene membrane transducer **1301**.

FIG. **23G** illustrates the positioning of a graphene membrane **2305** on top of the layered substrate shown in FIG. **23F** using techniques known in the art. The cavity formed below graphene membrane **2305** in FIG. **23G** is cavity **1401** of graphene membrane transducer **1301**.

FIG. **23H** illustrates depositing tungsten **2302** and then depositing oxide **2303** on top of the graphene membrane **2305** using techniques known in the art.

FIG. **23I** illustrates the layered substrate in which portions of the top layers of oxide **2303**, tungsten **2302**, and graphene membrane **2305** were removed by techniques known in the art to form a hole. This hole is vent hole **1402** of graphene membrane transducer **1301**. The portion of tungsten **2302** and graphene membrane **2305** that remains is the second metallic trace **1403** of graphene membrane transducer **1301**.

Because graphene is just a few angstroms thick and adheres closely to almost any material, it does not cause significant ripples in the materials deposited on top of it (and thus does not require CMP between layers). Even though it is thin, graphene is strong enough to hold up the weight of materials many times its own weight. Once a thin layer of material like metal is deposited (and solidifies) on top of graphene, this new material can help support subsequent layers of material.

FIG. **24** depicts a system **2400** showing a venturi effect. This system **2400** has an inlet orifice **2403** (having a cross-sectional area (A_1) **2401**), an outlet orifice **2405** (having a cross-sectional area (A_2) **2402**), and a venturi channel **2404**. The venturi channel **2404** is a constriction (i.e., the cross-sectional area of the venturi channel **2404** is less than cross-sectional area (A_1) **2401** and cross-sectional area (A_2) **2402**, such that the velocity **2406** of the fluid flow through venturi channel **2404** is much higher, as compared with the velocity **2406** in the inlet orifice **2403** and outlet orifice **2405**). The venturi channel **2404** also includes a venturi orifice **2410** that is exposed to a partial vacuum in the venturi channel **2404**. The partial vacuum is illustrated in FIG. **24** by the change in height **2407** of the fluid **2408** in the venturi orifice **2410** and the connection **2409** to the outlet orifice **2405**.

FIGS. **25A-25B** depict illustrations of a graphene membrane pump/transducer **2500** that utilizes a venturi channel **2504** and that show how graphene membranes **2509** move to cause fluid flow. FIG. **25A** illustrates the graphene membrane pump/transducer **2500** in the inflow process. Graphene membrane pump/transducer **2500** has an array of graphene membranes **2509** deflecting away from the substrate (i.e., to the left in the orientation of FIG. **25A**) and thus pulling a fluid (such as air) into pump orifice **2503** (having cross-sectional area (A_1) **2501**) via the venturi channel **2504**. This high velocity of fluid in the venturi channel **2504** (which can be, in some embodiments approximately 10-100 meters/second for air-flow) creates a partial vacuum within the venturi channel **2504** and as a result some fluid (such as air) is drawn into the venturi channel **2504** via the venturi orifice **2510**. The fluid flow in the pump orifice **2503**, the outlet orifice **2505**, and the venturi orifice **2510** are represented, respectively, by arrows **2506**, **2507**, and **2508**. The inflow of fluid (such as air) that passes through the pump orifice **2503** (having cross-sectional area (A_1) **2501**) is the sum of the air flowing in from the outlet orifice **2505** and the air drawn into the venturi orifice **2510**. Thus, the fluid flowing across cross-sectional area (A_1) **2503** is greater than the fluid flowing across cross-sectional area (A_2) **2505**.

FIG. **25B** illustrates the graphene membrane pump/transducer **2500** in the outflow process. When the graphene membranes **2509** move toward the substrate (i.e., to the right in the

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orientation of FIG. 25B) the direction of the fluid flow in the pump orifice 2503, the outlet orifice 2505, and the venturi channel 2504 reverses but the high velocity fluid moving through the venturi channel 2504 still creates a partial vacuum, which draws fluid into the venturi orifice 2510. The fluid flow in the pump orifice 2503 and the venturi orifice 2510 are represented, respectively, by arrows 2506 and 2508. The fluid flow in the outlet orifice 2505 is represented by arrows 2507A and 2507B. In the embodiment shown in FIG. 25B, the volume of fluid flowing through the pump orifice 2503 is less than the volume of gas flowing through the outlet orifice 2505.

Even though the air flowing through the pump orifice 2503 is on average zero (since the average inflow is equal to the average outflow), there is a net airflow that is exhausted through the outlet orifice 2505 due to the addition of the air flowing into the venturi orifice 2510.

This net airflow through the outlet orifice 2505 can be used to produce an audible sound wave (20 Hz to 20 kHz) even though the graphene membranes may have a mechanical frequency in the ultrasonic range (above 20 kHz). The average airflow exhausted through the outlet orifice 2505 can also be used to cool electronic components, produce thrust, or pump a fluid. Although an array of graphene membranes is shown in FIGS. 25A-25B, the graphene membrane pump/transducer 2500 would also operate with a single graphene membrane.

FIG. 26 depicts an electrically conductive membrane pump/transducer 2600 that utilizes an array of electrically conductive membrane pumps that cause a larger membrane 2602 to move in phase. Four of the electrically conductive membrane pumps of the electrically conductive membrane pump/transducer 2600 are illustrated in FIG. 26. Each of the electrically conductive membrane pumps has a membrane 2601 (such as a graphene-polymer membrane or metal-polymer composite membrane) that can deflect toward trace 2605 (as shown in the dashed curve 2601a) and that can deflect toward trace 2606 (as shown in the dashed curve 2601b). The traces 2604 and 2605 are a metal (like copper, tungsten, or gold). The electrically conductive membrane pumps also have a material 2603 (which can be plastic or Kapton) and material 2604 that is an electrical insulator (like oxide or Kapton).

Each of the electrically conductive membrane pumps in the array has chambers 2610 and 2611 that change in size as the electrically conductive membrane 2601 deflects between dashed curves 2601a and 2601b. As shown in FIG. 26, as electrically conductive membranes 2601 deflects toward trace 2605 (as shown in the dashed curve 2601a), (a) chamber 2610 reduces in size to expel air (or other fluid) through vent 2607 (and into chamber 2609) and (b) chamber 2611 increases in size to draw in air (or other fluid) through vent 2608. As electrically conductive membranes 2601 deflect toward trace 2606 (as shown in the dashed curve 2601b), (a) chamber 2610 increases in size to draw in air (or other fluid) through vent 2607 (and out of chamber 2609) and (b) chamber 2611 reduces in size to expel air (or other fluid) through vent 2608.

Chamber 2609 is bounded in part by the array of electrically conductive membrane pumps and a membrane 2602 (which is larger than the electrically conductive membranes 2601). Membrane 2602 can be made of a polymer material, like PDMS (polydimethylsiloxane) or latex. Membrane 2602 is generally on the order of 0.5 to 5 centimeters in diameter, and is much larger as compared to the electrically conductive membranes 2601, which are generally on the order of 0.5 to 5 millimeters in diameter. Typically, the ratio of the diameters between the membrane 2602 and the electrically conductive

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membrane 2601 is between 2:1 and 100:1, and more typically between 5:1 and 20:1. Vents 2607 allow air (or other fluid) be expelled into and withdrawn from chamber 2609 in response to the deflection of the electrically conductive membranes 2601 of the electrically conductive membrane pumps of the array.

The array of electrically conductive membrane pumps creates pressure changes in the chamber 2609 (increasing pressure as gas (or other fluid) is expelled into the chamber 2609 and reducing pressure as gas (or other fluid) is drawn out of the chamber 2609). These pressure changes cause membrane 2602 to move approximately in phase with the motion of the electrically conductive membranes 2601, which results in the desired audio frequency of the electrically conductive membrane pump/transducer 2600. I.e., the frequency of the mechanical deflections of the electrically conductive membranes 2601 equal the frequency of the mechanical deflections of membrane 2602, which in turn equals the desired audio frequency.

Benefits of electrically conductive membrane pump/transducer 2600 include that it produces on the order of 100 times more audio power than the electrically conductive membrane array does alone. This gain stems in part from the fact that audio power increases (for a fixed frequency and percent displacement of a given membrane) as the 5th power of membrane diameter, whereas the air volume required to move the large membrane 2602 increases as just the cube of membrane diameter. I.e., a given displaced air volume from the electrically conductive membrane pumps can be put to better use if it is used to move the membrane 2602.

Benefits of electrically conductive membrane pump/transducer 2600 also include that membrane 2602 can use very flexible material, like PDMS (since membrane 2602 is moved/driven by pressure changes that do not depend on the mechanical restoration force of membrane 2602) so that the displacement amplitude of membrane 2602 (audio power increases as the cube of membrane displacement) can be much higher than most other materials, including graphene or metals (such as copper). The net result is that this novel type of speaker can be much more compact than traditional (voice coil, etc.) speakers for a given audio power output.

Benefits of electrically conductive membrane pump/transducer 2600 also include that membrane 2602 can be much thinner than the cone of a voice coil because it is being moved by air pressure (which acts evenly on the entire membrane 2602). A thinner membrane means there is less inertia, which in turn means less power to drive/move membrane 2602 (which results in a higher system efficiency).

Benefits of electrically conductive membrane pump/transducer 2600 also include that there is no heavy copper voice coil attached to the larger membrane (as is used in the voice coil speakers in the prior art that presently dominate the commercial speaker market). For the same reasons as discussed above, less inertia (due to the absence of the heavy copper voice coil) leads to higher efficiency. A related benefit is no resistive heating losses of a copper voice coil (since no voice coil is needed).

Furthermore, there are a few reasons it is not practical to move membrane 2602 directly with an electrostatic force. First, the voltages would be too high, i.e., it would take several thousand volts to significantly move membrane 2602 that is just a few centimeters in diameter. Even if several thousand volts were available, it would likely cause an electrical arc within the air chamber. Second, it is difficult to make strong yet flexible membranes (such as graphene membranes) that are much larger than 1 mm in diameter. Third, it is difficult to drive membrane 2602 directly as it is likely to go into a

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runaway condition at high voltage and crash against the driving electrode. These limitations are overcome by using the air pressure of the electrically conductive membranes **2601** to mechanically move membrane **2602**. While other membranes, such as metal-polymer composite membranes, graphene membranes, graphene oxide membranes and graphene/graphene oxide membranes can alternatively be used, graphene-polymer membranes are generally used for the electrically conductive membranes **2601** because of the low gate voltages and because the array of small electrically conductive membrane pumps operate below the arcing threshold and membrane runaway is minimized.

Although FIG. **26** depicts electrically conductive membranes **2601** and membrane **2602** moving above and below their respective relaxed positions (as shown by curves **2601a** and **2601b** for electrically conductive membranes **2601** and curves **2602a** and **2602b** for membrane **2602**), electrically conductive membrane pump/transducer **2600** will also work (though it will produce less audio power) if each of electrically conductive membranes **2601** and membrane **2602** moves in one direction only (for example, upward in FIG. **26** as shown by curves **2601a** and **2602a**, respectively).

FIGS. **27A-27E** depict an electrically conductive membrane pump/transducer **2700** that, like the pump/transducer **2600**, utilizes an array of electrically conductive membrane pumps that cause a membrane **2702** to move in phase. FIGS. **27A-27B** are cross-sectional views of the pump/transducer that includes electrically conductive members **2701** (in the electrically conductive membrane pumps) and a speaker membrane **2702**. Speaker membrane **2702** can be made of a polymer, such as PDMS. Each of the electrically conductive membrane pumps has a membrane **2701** that can deflect toward downward (as shown in FIG. **26A**) and upwards (as shown in FIG. **26B**). Traces **2605** are a metal (like copper, tungsten, or gold). The electrically conductive membrane pumps also have a structural material **2703** (which can be plastic, FR4 (circuit board material), or Kapton) and support material **2704** that is an electrical insulator (like oxide, FR4, or Kapton). Support material **2704** can be used to support the pump membrane, support the stator and also serve as the vent structure. Integrating these functions into one element makes device **2700** more compact than it would be with multiple elements performing these functions. All of the non-membrane elements shown in FIG. **27** can be made from printed circuit boards, which enhances manufacturability.

Arrows **2706** and **2707** show the direction of fluid flow (i.e., air flow) in the pump/transducer **2700**. When the electrically conductive membranes **2701** are deflected downward (as shown in FIG. **27A**), air will flow out of the pump/transducer device **2700** (from the electrically conductive membrane pumps) as shown by arrows **2706**. Air will also flow from the cavity **2708** into the electrically conductive membrane pumps as shown by arrows **2707** resulting in speaker membrane **2702** moving downward. When the electrically conductive membranes **2701** are deflected upwards (as shown in FIG. **27B**), air will flow into the pump/transducer device **2700** (into the electrically conductive membrane pumps) as shown by arrows **2706**. Air will also flow into the cavity **2708** from the electrically conductive membrane pumps as shown by arrows **2707** resulting in speaker membrane **2702** moving upward.

FIG. **27C** is an overhead view of pump/transducer device **2700**. Line **2709** reflects the cross-section that is the viewpoint of cross-sectional views of FIGS. **27A-27B**. FIGS. **27D-27E** shows the flow of air (arrows **2707** and **2706**, respectively) corresponding to the deflection downward of electrically conductive membranes **2701** and speaker mem-

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brane **2702** (which is shown in FIG. **27A**). The direction of arrows **2707** and **2706** in FIGS. **27D-27E**, respectively, are reversed when the deflection is upward (which is shown in FIG. **27B**).

The basic operation for pump/transducer **2700** is the same as pump/transducer **2600** described above. A time-varying stator voltage causes the pump membranes **2701** to move and create pressure changes within the speaker chamber **2708**. These pressure changes cause the speaker membrane **2702** to move in synch with the pump membranes **2701**. This speaker membrane motion produces audible sound.

As with the pump/transducer **2600**, the sound power produced by the pump-speaker membrane system **2700** is much higher than the sound that is produced by the pump membranes **2701** acting alone. This "sound amplification factor" (the ratio of sound produced by the pump membranes **2701** acting through the speaker membrane **2702** as a system relative to the sound produced by the pump membranes acting alone) increases as the square of the pump membrane area divided by the speaker membrane area. For example, if the pump membrane area is 30 times the speaker membrane area (a typical ratio), the amplification factor is 900; the pump-speaker membrane system produces 900 times the sound power as the pump membranes do when acting on their own. The ability to stack pumps in a compact way greatly increases this amplification factor. Such a pump/transducer stacked system **2800** is shown in FIG. **28**.

For the embodiments of the present invention shown in FIGS. **27A-27E** and **28**, it has been found that the individual pump membranes **2701** can be smaller or larger than the speaker membrane **2702** and still obtain good performance. As discussed above, the total area of the pump membrane relative to the area of the speaker membrane influences performance.

Pump/transducer system **2700** (as well as pump/transducer speaker stacked system **2800**) can operate at higher audio frequencies due to axial symmetry (symmetrical with respect to the speaker membrane **2702** center). Each membrane pump is approximately the same distance from the speaker membrane **2702** which minimizes the time delay between pump membrane motion and speaker membrane motion (due to the speed of sound) which in turn allows the pumps to operate at higher pumping/audio frequencies than pump/transducer **2600**.

It also means that pressure waves from each membrane pump **2701** arrive at the speaker membrane **2702** at about the same time. Otherwise, an audio system could produce pressure waves that are out of synch (due to the difference in distance between each pump and the speaker membrane) and thus these waves can partially cancel (lowering audio power) at certain pumping/audio frequencies.

Pump/transducer system **2700** (as well as pump/transducer speaker stacked system **2800**) exhibits less out of phase "siren" sound (the sound made by time-varying high pressure airflow like a fire engine siren). The average velocity of the air outside of the speaker membrane chamber (at outer diameter of the pump/transducer system **2700**, which is shown by the arrows **2706** in FIG. **27E**) is lower than the average velocity of the air inside of the speaker membrane chamber (at the inner diameter of pump/transducer system **2700**, which is shown by the arrows **2707** in FIG. **27D**). Since the time-varying velocity of the air outside of the chamber produces sound (i.e., "siren sound") that is 180 degrees out of phase with the sound of the speaker membrane **2702** it should be minimized. The design of pump/transducer system **2700** does this by lowering the velocity of this external air (since this type of sound is proportional to the square of air velocity).

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Pump/transducer system **2700** (as well as pump/transducer speaker stacked system **2800**) further exhibit increased audio power. Since all the air enters/exits from the sides of the membrane pump (instead of the top/bottom like in pump/transducer system **2600**) these pumps can be easily stacked (such as shown in FIG. **28**) to significantly increase sound power. Increasing the number of pump stacks from one to four (as shown in FIG. **28**) increases audio power by approximately a factor of 64 (since audio power is proportional to the cube of speaker membrane displacement for a given frequency and displacement increases by a factor of four with four pump stacks). As a general rule, the audio power of the current invention increases roughly as the cube of the ratio of the pump membrane area to the speaker element area. One way to increase this area ratio without making the overall device wider is by stacking the membrane pumps. Stacking also minimizes the distance between each membrane pump **2701** and the speaker membrane **2702** (with associated advantages described above). As can be seen in FIG. **28**, the gas within the chamber is sealed by the membrane pump membranes and the speaker membrane. The gas in the sealed chamber can be air or another gas such as sulfur hexafluoride that can withstand higher membrane pump voltages than air.

Audio output is approximately linear with electrical input (resulting in simpler/cheaper electronics/sensors). Another advantage of the design of pump/transducer **2700** is the way the pump membranes **2701** are charged relative to the gates/stators. Applicant refers to these as "stators" since the term "gate" implies electrical switching. Pump/transducer **2600** (shown in FIG. **26**) has a low resistance membrane and the force between the stator and membrane is always attractive. This force also varies as the inverse square of the distance between the pump membrane and stator (and this characteristic can cause the audio output to be nonlinear/distorted with respect to the electrical input). The membrane can also go into "runaway" mode and crash into the stator. Thus, in practice, the amplitude of the membrane in pump/transducer **2600** is limited to less than half of its maximum travel (which lowers pumping speed and audio power).

The issues resulting from non-linear operation are solved in the design of pump/transducer **2700** by using a high resistance membrane (preferably a polymer film like Mylar with a small amount of metal vapor deposited on its surface) that is charged by a DC voltage and applying AC voltages to both stators (one stator has an AC voltage that is 180 degrees out of phase with the other stator). A high value resistor (on the order of 10^8 ohms) may also be placed between the high resistance membrane (on the order of 10^6 to 10^{12} ohms per square) and the source of DC voltage to make sure the charge on the membrane remains constant (with respect to audio frequencies).

Because the pump membrane **2701** has relatively high resistance (though low enough to allow it to be charged in several seconds) the electric field between one stator and the other can penetrate the charged membrane. The charges on the membrane interact with the electric field between stator traces to produce a force. Since the electric field from the stators does not vary as the membrane moves (for a given stator voltage) and the total charge on the membrane remains constant, the force on the membrane is constant (for a given stator voltage) at all membrane positions (thus eliminating the runaway condition and allowing the membrane to move within its full range of travel). The electrostatic force (which is approximately independent of pump membrane position) on the membrane increases linearly with the electric field of the stators (which in turn is proportional to the voltage applied to the stators) and as a result the pump membrane motion (and

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also the speaker membrane **2702** that is being driven by the pumping action of the pump membrane **2701**) is linear with stator input voltage. This linear link between stator voltage and pump membrane motion (and thus speaker membrane motion) enables a music voltage signal to be routed directly into the stators to produce high quality (low distortion) music.

FIGS. **29A-29B** depict an electrically conductive membrane pump/transducer **2900** that is similar to pump/transducer **2700**, in that it utilizes an array of electrically conductive membrane pumps. However, pump/transducer **2900** utilizes a more rigid structure **2901** (such as a lightweight piston) in place of a flexible speaker membrane (speaker membrane **2702** in FIGS. **27A-27E**). FIGS. **29A-29B** shows electrically conductive membrane pump/transducer **2900** utilizing a piston **2901**. While not illustrated in FIGS. **29A-29B**, pump/transducer system **2900** can use a simple spring mechanism to keep the piston centered when the device is off or the chamber is at atmospheric pressure during operation.

FIG. **30** depicts an electrically conductive membrane pump/transducer **3000** that is similar to the pump/transducers **2700** and **2900**, in that it utilizes an array of electrically conductive membrane pumps. Pump/transducer **3000** does not utilize a speaker membrane (such as in pump/transducer **2700**) or a structure in place of the speaker membrane (such as in pump/transducer **2900**). Pump/transducer **3000** produces substantial sound even without a speaker membrane (though the speaker membrane does provide increased audio power below about 100 Hz). Applicant believes the reason that there is still good sound power is that the membrane pumps are compressing the air as it makes its way out of the inner vents (increasing the pressure of an time-varying air stream increases its audio power). Arrows **3001** show the flow of air through the inner vents. The pump/transducer **3000** has a chamber that receives airflow **3001** and this airflow exhausts out the chamber by passing through the open area (the chamber exhaust area) at the top of the chamber. In order to produce substantial sound the total area of the membrane pumps must be at least 10 times larger than the chamber exhaust area.

FIG. **30** also shows an alternate vent configuration that has holes **3003** in the stators that allow air to flow to separate vent layers. The cross-sectional airflow area of the vents (through which the air flow is shown by arrows **3001**) is much smaller than the pump membrane area (so that the air is compressed). Furthermore, the outer vent area (which produces unwanted sound, and which the air flow is shown by arrows **3002**) is larger than the inner vent area (which produces desired sound) since the smaller airflow area of the inner vents results in increased pressure (and thus increased audio power). FIG. **30** also shows how a simple housing **3004** can direct the desired sound **3005** toward the listener (up as shown in FIG. **30**) and the undesired out of phase sound away from the listener (down as shown in FIG. **30**). The desired sound **3005** is in the low sub-woofer range to mid-range (20 Hz to about 3000 Hz).

FIG. **31** depicts an electrically conductive membrane pump/transducer **3100** that is the pump/transducer **3000** that also includes an electrostatic speaker **3101** (which operates as a "tweeter"). An electrostatic speaker is a speaker design in which sound is generated by the force exerted on a membrane suspended in an electrostatic field. The desired sound **3102** from the electrostatic speakers **3101** is in a frequency in the range of around 2 to 20 KHz (generally considered to be the upper limit of human hearing). Accordingly, pump/transducer **3100** is a combination system that includes a low/mid-range speaker and a tweeter speaker.

FIG. **32** depicts an electrically conductive membrane pump/transducer **3200** that is the pump/transducer **3100** that

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further includes the speaker membrane **3202** (such as in pump/transducer **2700**). Alternatively, pump/transducer **3200** could include a structure in place of the speaker membrane (such as piston **2901** in pump/transducer **2900**). The presence of the speaker membrane will additionally generate substantial lower frequency sounds (i.e., in the range of 20-200 Hz). Thus desired sound **3201** will include sounds from both the low/mid-range speaker of pump/transducer **3100** and also a powerful sub-woofer speaker. The speaker membrane **3202** can be selected to generate substantial audio power below 100 Hz (which is the range for consumer product sub-woofer), and even below 80 Hz (which is the range for professional live sound). Accordingly, pump/transducer **3200** is a combination system that includes a low/mid-range, tweeter, and sub-woofer speakers.

An embodiment of the pump/transducer **3200** was made using Mylar membranes. The Mylar membrane had a very thin coating of metal (gold or alternatively aluminum (that was vapor deposited on top of the Mylar in a chamber). This pump/transducer produced 30 micro-watts per cubic centimeter of pump assembly volume at 150 Hz, which is more than two times higher than the best commercial portable speaker. At 50 Hz, this pump/transducer producing about 2 micro-watts per cubic centimeter of pump assembly volume, which is more than 10 times higher than the best commercial portable speaker).

In addition to this improved audio power density, the pump/transducers of the present invention are unique from other speakers based upon the pressure they develop (particularly when operating in the 20-200 Hz frequency range). Small voice-coil cone speakers (with cone diameters on the order of three centimeters) operating at around 100 Hz reach pressure levels on the order of 1 Pa. Small electrostatic speakers (with membranes on the order of 3 centimeters in length/width) reach pressure levels of just 0.001 Pa at 100 Hz. The peak air pressure (occurring in the vents) of embodiments of the present invention that are similarly-sized are in excess of 10 Pa and can reach more than 100 Pa. Audio power is roughly proportional to developed air pressure. Accordingly, since the present invention is able to develop much higher pressures than other speakers its size, the present invention achieves significantly higher power for its size.

Furthermore, for a given frequency, the audio power of the present invention is proportional to airflow times the pressure. If the vent cross-sectional area is too small (for a given frequency), the pressure goes up but the airflow significantly decreases, which results in decreased audio. If the vent area is too large, the airflow increases but the pressure drops significantly, again resulting in a decrease of the audio power. Thus, for each frequency, there is a vent area optimal range (i.e., sweet spot) where the product of airflow and pressure is maximized.

Because there are a plurality of membrane pumps that can be uniquely addressed, different vent areas can be incorporated into the design of the pump/transducer system. Hence the present invention can include a variety of vent cross-sectional areas to optimize audio power across the entire audio frequency range (20 Hz to 20 kHz). For example, in a pump stack containing four membrane pumps (also called "pump cards") (as shown in FIGS. **28** and **30-32**), the vents thickness can be made as 125, 250, 375, and 500 microns (with a vent width of say 1 mm), respectively for membrane pumps **1-4**. Thus, the vent area for membrane pumps **1-4** would be 0.125, 0.25, 0.375, and 0.5 mm², respectively. A pump card can have on the order of 50 vents and so the total area of the vents in above example is 6.25, 12.5, 18.75 and 25 mm², respectively. In this example the membrane area of the

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membrane pumps within this same card is on the order of 1000 mm² or 40-160 times larger than the total card vent area. The widths of the vents could also or alternatively be varied to achieve the same or similar end. The key parameter is the cross-sectional areas of the vents.

The audio speaker can be used in any application that incorporates speaker devices. The speaker devices include for example loud speakers, car stereos, cell phones and MP3 players. The speaker devices can also be used in hearing aids and ear buds.

While embodiments of the invention have been shown and described, modifications thereof can be made by one skilled in the art without departing from the spirit and teachings of the invention. The embodiments described and the examples provided herein are exemplary only, and are not intended to be limiting. Many variations and modifications of the invention disclosed herein are possible and are within the scope of the invention. For example, both the small electrically conductive membranes and the larger membrane could be trough-shaped instead of round. In addition, there could be more than one larger membrane. Accordingly, other embodiments are within the scope of the following claims. The scope of protection is not limited by the description set out above, but is only limited by the claims which follow, that scope including all equivalents of the subject matter of the claims.

The disclosures of all patents, patent applications, and publications cited herein are hereby incorporated herein by reference in their entirety, to the extent that they provide exemplary, procedural, or other details supplementary to those set forth herein.

What is claimed is:

1. An audio speaker comprising at least one valve-less electrostatic pump, wherein each valve-less electrostatic pump comprises:

- (a) an electrically conductive membrane;
- (b) a first electrically conductive stator having a plurality of holes located on a first side of the electrically conductive membrane;
- (c) a second electrically conductive stator having a plurality of holes located on a second side the electrically conductive membrane;
- (d) a plurality of first support material members in contact with the first electrically conductive stator; and
- (e) a plurality of second support material members in contact with the second electrically conductive stator, wherein
 - (i) the plurality of the first support material members (A) support the first electrically conductive stator, (B) form a first vent structure operable to serve as the first vent structure, and (C) are positioned such that air can flow between the plurality of the first support material members in a direction that is substantially parallel to the first electrically conductive stator; and
 - (ii) the plurality of the second support material members (A) support the second electrically conductive stator, (B) form a second vent structure operable to serve as the second vent structure, and (C) are positioned such that air can flow between the plurality of the second support material members in a direction that is substantially parallel to the second electrically conductive stator.

2. The audio speaker of claim 1, wherein air can flow through the holes of the first electrically conductive stator and the second electrically conductive stator.

3. The audio speaker of claim 1, wherein the electrically conductive membrane comprises a polymer and an electrically conductive material.

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4. The audio speaker of claim 3, wherein the electrically conductive membrane has an electrical resistance in excess of one million ohms per square.

5. The audio speaker of claim 1 further comprising a pump stack wherein the pump stack comprises a plurality of valve-less electrostatic pumps.

6. The audio speaker of claim 5, wherein each of the valve-less electrostatic pumps in the pump stack is operable to be individually addressed with a voltage.

7. The audio speaker of claim 1, wherein the at least one valve-less electrostatic pump comprises at least one valve-less annular electrostatic pump.

8. The audio speaker of claim 7 further comprising an annular pump stack, wherein the annular pump stack comprises a plurality of valve-less annular electrostatic pumps.

9. The audio speaker of claim 1, wherein the at least one valve-less electrostatic pump comprises at least one valve-less curved electrostatic pump.

10. The audio speaker of claim 9 further comprising a curved pump stack, wherein the curved pump stack comprises a plurality of valve-less curved electrostatic pumps.

11. The audio speaker of claim 1, wherein

(a) the electrically conductive membrane is flat when in its relaxed position;

(b) the plurality of the first support material members is a plurality of first curved support material members; and

(c) the plurality of the second support material members is a plurality of second curved support material members.

12. An audio speaker comprising a stack of at least four valve-less electrostatic pumps wherein each of valve-less electrostatic pumps comprises:

(a) an electrically conductive membrane;

(b) a first electrically conductive stator having a plurality of holes located on a first side of the electrically conductive membrane;

(c) a second electrically conductive stator having a plurality of holes located on a second side the electrically conductive membrane;

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(d) a plurality of first support material members in contact with the first electrically conductive stator; and

(e) a plurality of second support material members in contact with the second electrically conductive stator, wherein

(i) the plurality of the first support material members (A) support the first electrically conductive stator, (B) form a first vent structure operable to serve as the first vent structure and (C) are positioned such that air can flow between the plurality of the first support material members in a direction that is substantially parallel to the first electrically conductive stator; and

(ii) the plurality of the second support material members (A) support the second electrically conductive stator, (B) form a second vent structure operable to serve as the second vent structure and (C) are positioned such that air can flow between the plurality of the second support material members in a direction that is substantially parallel to the second electrically conductive stator.

13. The audio speaker of claim 12, wherein each of the valve-less electrostatic pumps within the stack is operable to be individually addressed with a voltage.

14. The audio speaker of claim 12, wherein the electrically conductive membrane of each of the valve-less electrostatic pumps is mechanically separated from the electrically conductive membranes of the other valve-less electrostatic pumps within the stack.

15. The audio speaker of claim 12, wherein

(a) the number of the first support material members in the plurality of the first support material members is more than two; and

(b) the number of the second support material members in the plurality of the second support material members is more than two.

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